EXPORING EVIDENTIARY REASONING INSTRUCTION IN UNDERGRADUATE BIOLOGY LABS

by

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For my mom, Huijun Li, a strong woman who gave me life and endless love.

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ABSTRACT

Recent trends toward engaging undergraduate biology students in scientific investigations have shifted focus toward helping students understand and use scientific evidence. Instructors must promote students' evidentiary reasoning as they generate, use, and evaluate scientific evidence during the investigations. However, explicit guidance is needed for instructors to address students' difficulties in understanding and using evidence when they are constructing claims and explanations in the scientific investigations. To unpack the complexity of evidentiary reasoning, my dissertation research was informed by the Conceptual Analysis of Disciplinary Evidence (CADE) framework, which I applied to the context of biology instructor professional development with three studies: two studies used the CADE framework as a lens to modify teaching of Hardy-Weinberg Equilibrium (HWE) and structural biology investigations and to provide lab instructors with support in guiding evidentiary reasoning for their students in an introductory biology course; a third study explored evidentiary reasoning practices according to interviewed members of the Faculty Developer Network for Undergraduate Biology Education (FDN-UBE).

With CADE as a framework, a novel HWE lab investigation was developed which highlighted evidentiary reasoning. Across three semesters, scaffolding questions to prompt reasoning with and about scientific evidence were changed in collaboration with lab instructors during professional development training with the CADE framework. Actual lab discussions were recorded to examine changes in the prompts implemented by one instructor. Findings showed that the instructor delved deeply into more facets of the evidence with the CADE framework. The lab instruction was intended to direct students to consider multiple aspects of evidentiary reasoning in a way that integrated their disciplinary knowledge with epistemic considerations about the nature, scope and quality of scientific evidence.

Structural biology investigations were modified in the second study in collaboration with graduate teaching assistants (GTAs) after a series of professional development trainings with the CADE framework. Lab discussions were recorded in four lab sections taught by two GTAs: one was a structural biologist and one was not. Each guided lab discussion in their two sections by leading evidentiary reasoning discussions in different ways: (a) with general evidence scaffolds (GES) and (b) with disciplinary evidence scaffolds (DES). Analysis of the lab discussions and interviews show that the GTAs' instruction about evidentiary reasoning reflected their preferences

and beliefs about the types of scaffolding questions they were using. With the GES, the instruction shifted from GTAs mainly introducing their own thoughts to more prompting of students to think and reason with evidence.

A third study employed the CADE framework as a lens to reveal evidentiary reasoning practices from interviews with members of Faculty Professional Developer Network for Undergraduate Biology Education (FDN-UBE). By coding segments of their interviews into CADE categories, I found that FDN-UBE members emphasized learning disciplinary knowledge, but with attention to further developing students' epistemic reasoning and evidentiary reasoning and many emphasize the social dimensions of biological investigations.

In summary, findings from these three studies provide practical examples of instructors prompted students to use scientific evidence in terms of integrating epistemic considerations with disciplinary knowledge for evaluating development of evidentiary reasoning (or lack thereof) when students engage with biological investigations in undergraduate labs. The CADE is a systematic framework that supported a shift in professional practice toward more sophisticated epistemic reasoning in the teaching and learning of biology. The findings also provide implications for faulty professional development for supporting teaching about evidentiary reasoning in the future.

CHAPTER 1. INTRODUCTION

1.1 Scientific Evidence and Evidentiary Reasoning

Recent trends in engaging biology students in scientific investigations have focused more on helping undergraduate students understand and use scientific evidence in their biology courses. This is primarily due to the essential role of scientific evidence in knowledge construction in biology disciplines. Scientific evidence refers to the data that are used for addressing a research question, supporting or refuting a claim (NGSS, 2013). Derived from the coordination of the models of theories and methodologies, scientific evidence serves in a role that allows scientists to evaluate the similarity between the theories and the real world (Giere, 2006). Evidentiary reasoning plays an important role during generating, using and evaluating scientific evidence to solve problems and make claims. In this process students need to reason with and about scientific evidence in order to understand the nature, scope and quality of evidence (Samarapungavan, 2018; Wills, 2018).

Numerous studies have focused on student's using evidence when they write explanations and claims. Despite the efforts on advancing evidentiary reasoning in science education, studies show that students still struggle in understanding and use evidence. This is partially due to the complex nature of scientific evidence in that scientific evidence is multifaceted. The generation, use and evaluation of evidence are related to multiple scientific practices and various theoretical and methodological knowledge, including the techniques used for collecting evidence, the statistical methods for analyzing evidence, etc. (Samarapungavan, 2018). Another reason is that the scientific evidence used in the classroom education has usually been treated in simplified and insufficient ways. Students rarely encounter authentic evidence and have few opportunities to practice evidentiary reasoning with authentic evidence in connecting necessary disciplinary knowledge with epistemic considerations for evaluating the nature, scope and quality of evidence (Duncan et al., 2018). Additionally, the studies about scientific evidence and evidentiary reasoning have focused more on using evidence in making explanations and claims, and the analysis has been based on the structure of claims, for example using Toulmin's argumentation patterns (Toulmin, 1958). Thus, there is a need to study how to advance students' understandings about the process of scientific evidence generation or construction through their scientific investigations.

1.2 Instructional Support for Evidentiary Reasoning

Explicit instructional supports, including well-designed learning environment and instructor's facilitation, are indispensable for guiding students to understand and use scientific evidence with development of their evidentiary reasoning skills (Manz, 2016). A learning environment which provides students with authentic scientific activities has been reported to have positive influences on development of scientific reasoning skills. Studies show that through inquiry-based learning, students showed greater gain in conceptual knowledge, as well as reasoning ability (Furtak et al., 2012; Gerber et al., 2001; Jensen & Lawson, 2011). Authentic scientific research in the learning environment such as inquiry-based learning provides students with the chance to practice solving problems, testing hypotheses, generating evidence to draw conclusions, in ways that are similar to processes that professional scientists engage in for new knowledge construction (Chinn & Malhotra, 2002; French & Russell, 2002). These activities are essential for helping students use and reason with and about evidence, during which they get the opportunity to understand the construct of scientific evidence as well as science knowledge. Thus, learning through scientific inquiries or investigations provides the needed learning environment for supporting students' evidentiary reasoning ability. The instructor also plays a crucial role in supporting student learning through guiding them during scientific investigations. They help students make connections between activities and science concepts and principles to support students' conceptual understanding (Puntambekar et al., 2007), they engage students in argumentation by justifying their claims, and they guide debating of alternative explanations (Osborne et al., 2004; Tabak & Baumgartner, 2004).

To address the important role of instructional supports for advancing students' reasoning skills, in this dissertation, I focus on designing new approaches to guide instructors in advancing students' evidentiary reasoning during their scientific investigations in undergraduate biology lab research courses. The instructional strategies that I focused on in this dissertation is scaffolding. Scaffolding as a metaphor in education refers to the process of teachers or experience peers using temporary support to help students complete tasks that may beyond students competences (Wood et al., 1976). Based on the positive impact of scaffolding questions on students' learning (Belland et al., 2008; Ge & Land, 2003), the chapters in my dissertation explored how instructors can integrate more evidentiary reasoning through the scaffolding approach into their instruction during scientific investigations in different biology sub- disciplinary contexts.

1.3 The Conceptual Analysis of Disciplinary Evidence (CADE) Framework

The main theoretical framework of this dissertation is the Conceptual Analysis of Disciplinary Evidence (CADE) framework (Samarapungavan, 2018). The CADE framework helps unpack the construct of scientific evidence into four practices which well aligned with the process of scientific investigation, from articulating the model for guiding the investigation (Theory => Evidence relationships) to generating scientific evidence by designing, executing and analyzing investigation models (Evidence <=> Data relationships), and then drawing conclusions with the scientific evidence to argument models (Evidence => Theory relationships) and at all stages of the investigation, communicating about the research and the generated evidence in the public sphere (Social dimensions). These practices under the four relationships are interrelated, indicating that the use of scientific evidence is complex and multifaceted in relationship to the various theoretical and methodological models and scientific practices. The CADE also links evidentiary reasoning to the interaction of disciplinary knowledge with epistemic considerations as two essential components for evidentiary reasoning. This highlights the important role of disciplinary knowledge in guiding students' evidentiary reasoning.

Unlike other published frameworks or models that analyze students' use of scientific evidence for making claims and argumentation approaches that focus on the structure and components of a single claim or argument (e.g. Brown et al., 2010; Toulmin, 1958), the CADE framework focuses on the process of generating and using scientific evidence, which happens at all stages of the scientific investigation. This emphasis is well aligned with a recent trend toward implementation of Course-based Undergraduate Research Experiences (CUREs) in undergraduate lab investigations where students involved with use of science practices, collaboration, discovery about a topic of broad relevance, and iteration to engage students in learning the research process and how to conduct their own investigations (AAAS, 2011; Auchincloss et al., 2014; Linn et al., 2015; Rodenbusch et al., 2016). Studies have shown that CUREs have multiple positive impacts on students' learning. For example, students' conceptions of thinking like a scientist and practice of scientific thinking have been improved after engaging in a CURE lab (Brownell et al., 2012). Moreover, a CURE repeatedly leads to more inclusive instruction in science education because it allows the access to research by a diverse student population (Bangera & Brownell, 2014; Gin et al., 2018). The ability of CUREs to provide a large number of students with authentic research experiences make it an ideal context for studying tutoring and training of evidentiary reasoning using the CADE framework.

1.4 Research Problem

With the emphasis on scientific evidence and evidentiary reasoning, this dissertation aims to explore instructional methods for supporting instructors in facilitating undergraduate students toward a deep understanding of scientific evidence and developing sophisticated evidentiary reasoning during scientific investigations in the lab course environment. The CADE framework was implemented into multiple aspects of instruction for undergraduate biology lab courses as a practical guide for understanding and using scientific evidence.

1.5 Outline of the Dissertation

This dissertation consists of manuscripts of three qualitative studies. Chapter 2 and chapter 3 present two studies that implemented the CADE framework for supporting instruction on evidentiary reasoning, which were conducted in an introductory biology laboratory course required for all biology major students at an American research-intensive institution in the Midwest. The lab course modules were set up informed by the literature of CUREs.

Chapter 4 presents a study used the CADE framework as an analytical lens to reveal evidentiary reasoning practices from the members of the Faculty Professional Developers Network for Undergraduate Biology Education (FDN-UBE), a national network for advancing professional development for undergraduate biology education. This study provided understanding of instructors' evidentiary reasoning practices in a broader context.

1.5.1 Introduction to chapter 2, integrating evidentiary reasoning in teaching Hardy-Weinberg equilibrium

Chapter 2 is a manuscript about use of the CADE as a framework for guiding modification and implementation of an undergraduate lab module and the way in which instructors guided lab discussions, titled "The Conceptual Analysis of Disciplinary Evidence (CADE) framework as a guide for evidentiary reasoning: A practical implementation in a Hardy-Weinberg Equilibrium (HWE) lab investigation". This study features instructional designs informed by the CADE framework to support an instructor who guided students to use scientific evidence and engage in evidentiary reasoning during the lab investigation. It also provides a practical example of implementing the CADE framework in professional development to influence of lab instruction during the HWE investigation. Teaching assistants as the lab instructors were invited to participated in this study to implement the CADE framework in guiding the HWE investigations. Lab instructions across three semesters were recoded and transcribed. One of the participating instructor's lab discussions were used as the one practical example. This study aimed to answer the research question:

How did implementing the CADE framework influence the lab instruction on scientific evidence during the HWE lab investigation?

Starting with a review of published HWE activities, this study identified the lack of evidentiary reasoning as a learning objective in these HWE activities. A modified lab investigation along with the assessment for teaching HWE was developed informed by the CADE framework. This novel HWE lab investigation highlighted evidentiary reasoning as a learning objective, and provided students with detailed disciplinary knowledge underpinning their investigation and evidentiary reasoning. With well-designed scaffolding questions that explicitly target at prompting students' evidentiary reasoning, the instructor could encourage students to generate, use and evaluate scientific evidence when engaging in hypothesis testing processes.

Influences of guiding the professional development using the CADE framework to steer lab instruction toward evidentiary reasoning were reported as a practical demonstration. Changes from one instructor's lab instruction before and after the CADE implementation were described. After going through the professional development activities, the instructor led more discussions that directed students to consider multiple aspects of evidentiary reasoning, and encouraged students' epistemic considerations about the nature, scope and quality of scientific evidence. These changes suggested that the CADE framework could be a practical pedagogical tool to help instructors develop and implement questions to guide students' evidentiary reasoning by combing epistemic considerations with disciplinary knowledge in a scientific investigation.

1.5.2 Introduction to chapter 3, integrating evidentiary reasoning in teaching structural biology

Chapter 3 is the manuscript of the study, titled "Implementing the Conceptual Analysis of Disciplinary Evidence (CADE) framework in the instruction of a structural biology lab investigation". In this study, two graduate teaching assistants (GTAs) from different research backgrounds were invited to participate in a series of professional development (PD) trainings that introduced them to the CADE framework. One GTA was a graduate student in structural biology and served as the content expert for creating the lab material for the structural biology module. The other GTA was a graduate student in a botany doctoral degree program. Participating GTAs developed two types of scaffolding questions: general evidence scaffolds (GES) and disciplinary evidence scaffolds (DES) questions and implement these questions in different sections to guide the structural biology lab investigation. Lab instruction for four sections (one GES and one DES for each GTA), together with the interviews of the participant GTAs were recorded and transcribed. This study aimed to answer two research questions:

1. How did the two GTAs lead the discussions on evidentiary reasoning guided by the CADE framework during the structural biology investigation?
2. How did GES and DES influence the GTAs' instruction during the structural biology investigation?

Comparison of the lab instruction and interviews of the two participating GTAs showed that the GTAs' prior knowledge and their preferences about GES and DES affected the way they guided discussions on the evidentiary reasoning. Despite that the disciplinary knowledge is essential to developing successful reasoning, GES could help shift the GTA's instruction from focusing on introducing their own ideas about the advanced disciplinary knowledge, which may beyond students' understanding and lead to lacking in the necessary epistemic considerations for evidentiary reasoning, to introducing and prompting students' idea about the general hypothesis testing and reasoning strategies. Unpacking GTAs instructions using the CADE framework demonstrated that GTAs still focused primarily on the disciplinary knowledge aspect of the evidentiary reasoning, and barely talked about epistemic considerations. These results provided implications for supporting teaching evidentiary reasoning in the future.

1.5.3 Introduction to chapter 4, understanding evidentiary reasoning practices from members of FDN-UBE

Chapter 4 is a book chapter that written about a study, titled "Biological reasoning according to members of the faculty developer network for undergraduate biology education: Insights from the Conceptual Analysis of Disciplinary Evidence (CADE) framework". Using the CADE framework as a theoretical lens, this study revealed evidentiary reasoning practices from the profession developers' perspective. Members of the Faculty Processional Developer Network for Undergraduate Biology Education (FDN-UBE) were invited to be interviewed about their motivations and experiences for engaging in the professional development for undergraduate biology education. From their experiences in advancing undergraduate biology education, this study aimed to answer the following research questions:

1. What personally motivates/motivated network members to engage in professional development?
2. What professional paths did they take along the way to becoming interested in and effective at professional development for biology faculty?
3. What resources or indicators of success make FDN-UBE members feel qualified to be leading effective faculty development?
4. What model of professional practice represents the value added and additional potential contributions from FDN-UBE members who are engaged in biology faculty professional development to advance undergraduate biology education?

Findings from interviews reveal that these professional developers are valuable visionaries. Usually going through non-conventional career pathways, these professional developers disseminate knowledge via biology faculty professional development, and their knowledge sources are not limited to the professional development literature. They value the role of authentic research in learning biology. With the expertise in both scientific research and biology education, their experiences and suggestions for teaching evidentiary reasoning, including enhancing the foundation of disciplinary knowledge, providing opportunities for practicing analysis with authentic data, helping students understand the sufficiency of interpretations and encouraging students to communicate evidence to the public, could become valuable resources for other faculty who want to engage in biology education and include evidentiary reasoning in their teaching.

1.5.4 Introduction to chapter 5, conclusion

Chapter 5 is the conclusion chapter that summarized conclusions, contributions as well as limitations of each study in this dissertation. Future directions for advancing evidentiary reasoning in undergraduate biology education were also discussed in this chapter.

In summary, findings from the three studies presented in this dissertation provided practical examples of instructors prompted students' evidentiary reasoning via integrating disciplinary knowledge with epistemic considerations guided by the CADE framework. The CADE framework is a guide for shifting professional practice toward more sophisticated evidentiary reasoning in the teaching and learning of biology. Findings from these studies also provided implications for supporting instructors guiding evidentiary reasoning through professional development with the CADE framework in the future.

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CHAPTER 2. THE CONCEPTUAL ANALYSIS OF DISCIPLINARY EVIDENCE (CADE) FRAMEWORK AS A GUIDE FOR EVIDENTIARY REASONING: A PRACTICAL IMPLEMENTATION IN A HARDY-WEINBERG EQUILIBRIUM (HWE) LAB INVESTIGATION

2.1 Introduction

2.1.1 Scientific Evidence and Evidentiary Reasoning

As we enter the era of "big data" and the rapid advancement of the digital world, people are constantly challenged to evaluate data as evidence and make informed decisions that impact both daily and professional life (Barzilai & Chinn, 2020; Labrinidis & Jagadish, 2012; Marx, 2013). For example, during the COVID-19 pandemic, information about the current situation was posted on TV shows, newspapers, social media, and reports from government officials. However, even information from the most widely trusted resource is prone to error and can be interpreted differently by different people (Zarocostas, 2020). Thus, educating the public and the future citizens how to properly evaluate evidence poses great challenge to the tertiary level education (Barzilai & Chinn, 2020; Chinn et al., 2020). There is a need for studies on how to equip the students at tertiary level especially in STEM areas with the fundamental competency of understanding and using scientific evidence which will benefit their professional development as well as daily life.

From the perspective of science education, scientific evidence is based on data that are used to address a question or used in the process of supporting a claim (NGSS, 2013; Sandoval & Reiser, 2004). Scientific evidence in authentic research is usually generated with various technologies and methods that rely on multiple types of disciplinary knowledge and practices. In real investigations, the evidence for claims varies in amount, scope, and comprehensiveness, whereas scientific evidence used in the science classroom is often more simplified in forms and usages (Chinn & Malhotra, 2002; Duncan et al., 2018). During science learning, students rarely encounter the kind of complex and more contentious evidence that scientists often encounter in their research. The gap that exists between the simplified evidence used in science education and the actual complexity of scientific evidence that exists in the real world increases the difficulty for students to understand scientific evidence as well as to develop evidentiary reasoning ability, which refers to the competence of reasoning with and about scientific evidence in their science learning (Duncan et al., 2018; Samarapungavan, 2018). Helping students properly understand, use and reason with scientific evidence in the process of investigation also presents a challenge for the instructors who guide the investigations.

Despite numerous reports on attempts to improve students' evidentiary reasoning ability, studies have revealed that students still had problems with understanding and using evidence. Sandoval and Millwood (2005) showed that middle school students often failed to cite sufficient evidence when writing explanations for natural selection problems, and the students did not articulate the connection between the specific evidence and the claims. In the context of atmospheric science, Jeong, Songer, and Lee (2007) analyzed forty sixth grade students' responses to the test of reasoning skills involved in the collection, organization and interpretation of data contextualized in atmospheric science. They found that students' understanding of scientific evidence and reasoning skills regarding the data collection process were quite weak in several important aspects, including appreciating the importance of scientific evidence, identifying the relevant evidence, and properly interpreting examples and tables. By analyzing argumentations within peer-led sessions in small groups in an undergraduate chemistry course, Kulatunga, Moog, and Lewis (2013) found that although students could support their arguments with evidence and reasoning, their answers often lacked elaboration on reasoning and further validation on explanations. These studies show that students not only need help in conceptual understanding of scientific evidence, but more importantly they could be benefit from explicit instruction of practices that use scientific evidence.

The importance of learning science through scientific investigation has been emphasized in the recent decade. Increasing encounters with scientific investigations in biology classrooms and laboratories could help students improve their understanding of core concepts (AAAS, 2011), grasp basic scientific competencies in experimentation (Pelaez et al., 2017) and cultivate biological literacy (AAAS, 2011). The ability to understand and use scientific evidence as an essential component of scientific investigation is gaining focus as a foundation of undergraduate biology education (AAAS, 2011; Laursen 2019). However, we do not yet know whether the trend towards engaging undergraduate students with scientific investigations yields gains similar to those from other instructional methods that have been reported to have a positive influence on learners' scientific reasoning ability (Blumer & Beck, 2019; Gerber et al., 2001; Jensen & Lawson, 2011;

Wilson et al., 2010). The cultivation of competent thinking and evaluation of scientific evidence has become a crucial problem for educational research and instructors in higher education. Since scientific reasoning ability may not develop naturally among most students when exposed to traditional curriculum (Kuhn, 2009), there is a need for including evidentiary reasoning as one of the learning objectives in science education.

In this study, a novel laboratory investigation for teaching Hardy-Weinberg Equilibrium (HWE) is presented in this study, which aiming at prompting students' evidentiary reasoning by implementing the Conceptual Analysis of Disciplinary Evidence (CADE) framework. We also presented a practical example of one instructor participated in the professional development with the CADE framework and implemented the CADE in her instruction when guiding the HWE investigation. From the comparison of instructions before and after the CADE framework implementation, this study aims to answer the research question: How did implementing the CADE framework influence the lab instruction on scientific evidence during the HWE lab investigation? The HWE and the CADE framework will be introduced in the next section.

2.2 Scaffolding in Science Education

Scaffolding is a metaphor in education that refers to the process of teachers or knowledgeable peers using temporary supports to help learners complete tasks that may be beyond the learners' independent capacity (Wood et al., 1976). Scaffolding is derived from Vygotsky's notion of the Zone of Proximal Development (ZPD) which refers to "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem-solving under adult guidance, or in collaboration with more capable peers"(Vygotsky, 1978, p. 86). Through scaffolding, learners can receive supports from conceptual (what to consider), metacognitive (how to think during learning), procedural (how to use tools) and strategic (strategies in approaching tasks or problems) perspectives (Hannafin et al., 1999).

Prompts, hints and questions are useful scaffolding strategies. Instructional questions and prompts have been reported to have significant positive effects on students' performance on problem-solving and evidence-based argumentation, including representing the problem, identifying relevant information, gathering evidence to solve problems, generating hypotheses and linking evidence to claims (Belland et al., 2008; Ge & Land, 2003; van Joolingen & De Jong, 1991). For example, in the context of information sciences and technology, Ge and Land (2003) provide examples of specific questions they used to prompt thinking about their work on a problem as the students independently worked through and discussed ideas with peers. They found that students who received such questions and prompts were able to clearly represent the problem and identify the relevant information when solving the problem. However, the example questions used by Ge and Land (2003) do not specifically target the important role of evidence nor did those questions direct students toward evidentiary reasoning appropriate for a laboratory investigation. Therefore, as a first step to guide students' thinking and reasoning with and about scientific evidence during the process of scientific investigation, there is a need to clarify how reasoning with and about scientific evidence happens throughout the entire research process.

2.3 The Conceptual Analysis of Disciplinary Evidence (CADE) Framework

One useful framework for unpacking evidentiary reasoning in the entire process of scientific investigation is the Conceptual Analysis of Disciplinary Evidence (CADE) framework (Samarapungavan, 2018), it could benefit instructors in developing questions and prompts to scaffold students' evidentiary reasoning during scientific investigations. The CADE framework unpacks evidentiary reasoning into four relationships: the Theory => Evidence relationships refer to the practice of formulating testable hypotheses, explanations or rationale for an investigation; the Evidence <=> Data relationships refer to the practice of designing, executing, and analyzing investigation models; the Evidence => Theory relationships refer to models of inference, argumentation and discussions about the uncertainty or sufficiency of conclusions, and the Social Dimensions refer to the communication of evidence throughout the research process in a public sphere. These four relationships indicate that evidentiary reasoning happens throughout the entire process of the scientific investigations, from identifying important unsolved problems, choosing theoretically important variables, collecting data to contribute as evidence to test hypotheses, drawing conclusions based on the evidence and communicating the research plans and results in the public or with other scientific researchers.

Within each of the four relationships, the CADE framework focuses on two essential components of reasoning with and about scientific evidence: disciplinary knowledge and epistemic considerations. Disciplinary knowledge provides the foundation for the investigation. The theories or assumptions that one person has will affect the person's decisions about what to choose as evidence, how to use the evidence, and what can be drawn as conclusions from the evidence. Epistemic considerations throughout all four relationships of evidentiary reasoning relate to ideas about the scope, quality and limitations of the theories, evidence and conclusions, it closely related to critical thinking. When practicing a scientific investigation, investigators need to not only grasp the disciplinary knowledge that is necessary to conduct the investigation, like the theories and models that are underlying the investigation, the variables that are relevant to the research question, but also how to evaluate the quality of the scientific evidence, including the reliability of the evidence, as well as the precision and accuracy of the techniques and equipment used. Thus, the disciplinary and epistemological aspects of evidentiary reasoning are inter-related when one's doing evidentiary reasoning. From the educational perspective, instructors need to not only introduce students with the disciplinary knowledge that is necessary to conduct the investigation, but also need to implement curriculum and instructional methods to support students' epistemic considerations for preparing students' critical thinking in both the scientific learning and their daily life (Barzilai & Chinn, 2018; Chinn et al., 2020). In each relationship and under each component, the CADE framework poses several questions regarding important features of scientific evidence. Although the CADE framework is built on examples from biology, the proposed questions, especially questions of relevance to epistemic considerations are very general and are intended to be applicable in many different contexts and disciplines.

In summary, the CADE framework is intended to provide an efficient guide for both instructors and learners to understand the construct of scientific evidence and evidentiary reasoning. Since the context for this study is a scientific investigation in an undergraduate biology lab course, we only focus on the first three relationships in the CADE framework in this article, as these represent what happened during the laboratory investigation.

2.4 The Hardy-Weinberg Equilibrium (HWE) Instruction

2.4.1 Published HWE instruction examples

The Hardy-Weinberg Equilibrium (HWE) is a fundamental model for population genetics that was first demonstrated separately by two scientists, G. H. Hardy and Wilhelm Weinberg, in the early 20th century (Hardy, 1908; Stern, 1943; Weinberg, 1908). According to this model, for a Mendelian trait that contains two alleles at one locus, one a dominant allele and another the recessive allele, the allele frequencies will remain constant across generations in a population if certain conditions are met (Figure 2.1). The conditions include no mutation in the gene, random mating between the individuals in the population, every individual produces the same number of offspring, no gene flow into or out of the population, infinite population size and no occurrences of natural selection. No evolution occurs in the population if it is in HWE, therefore understanding HWE is critical to grasp the ideas and core concepts of evolution (Wise, 2018b). For this reason, HWE is often taught as a fundamental introduction to population genetics in many introductory-level biology courses. By tracking changes in allele frequencies for a population over time, HWE helps students appreciate that evolution is not only the development of new species from existing ones, but can also be the result from the changes in the allele frequencies within a population over a long period of time. The topic of HWE in undergraduate biology education provides a foundation for the increasingly important discipline of evolutionary biology. By including the HWE, instructors also address the call to connect the use of mathematics with learning about biological phenomena (AAAS, 2011; Schuchardt & Schunn, 2016; Speth et al., 2010; Wise, 2018b).

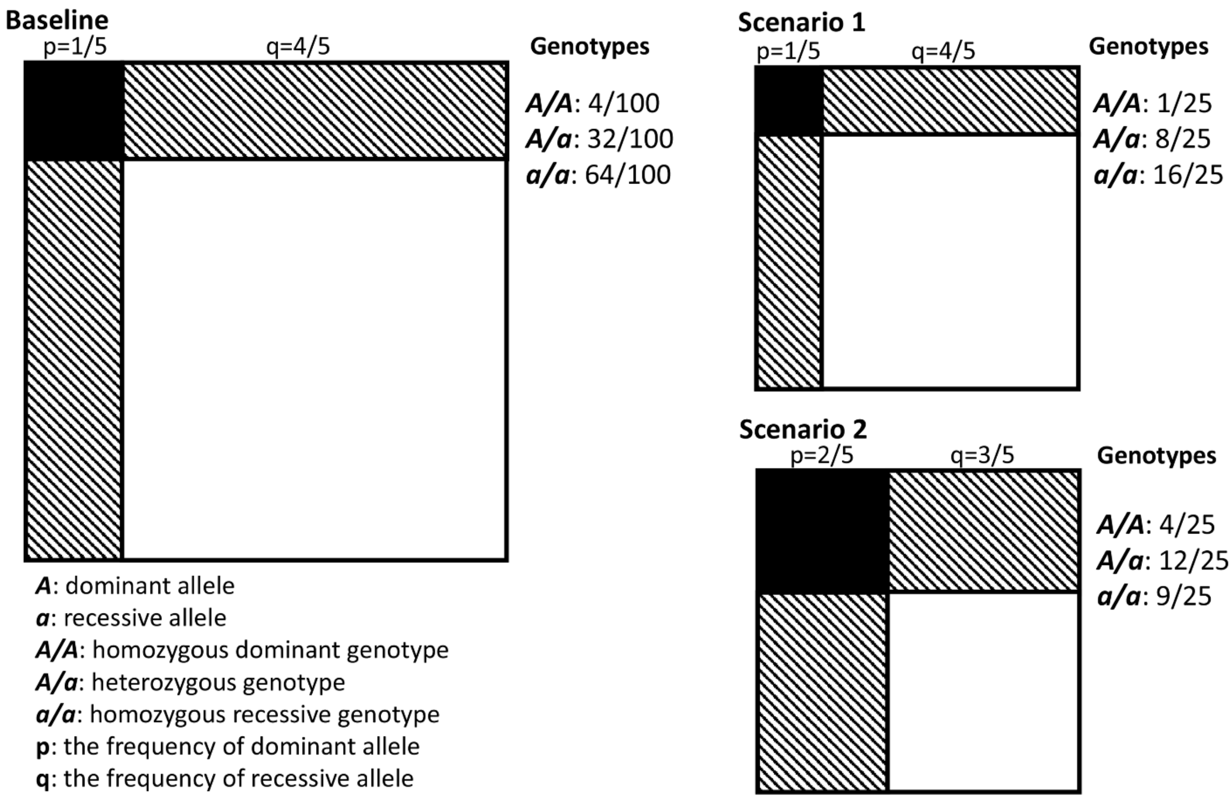

Figure 2.1. Illustration of a population change where Scenario 1 could be in Hardy-Weinberg equilibrium (HWE) but Scenario 2 is not. This figure compares two scenarios of hypothetical populations with the focus on one Mendelian trait. One population maintains a phenotype ratio of 36% dominant and 64% recessive from Baseline to Scenario 1 so it could have remained in Hardy-Weinberg Equilibrium (HWE) whereas the second illustrates a change not in HWE where the dominant phenotype increased to 64% with only 36% of the population still showing the recessive phenotype. Appendix A provides a Student Handout for use with this figure.

Despite the importance of introducing HWE in undergraduate biology laboratory courses, several studies indicate that students show difficulty in understanding and applying HWE even when they have remembered and can use the HWE equation ($p^2 + 2pq + q^2 = 1$) for calculating problem solutions. Reports show that students have difficulty understanding an underlying biological phenomenon of relevance to HWE (Masel, 2012; Smith & Baldwin, 2015). To address this problem, researchers and instructors have designed and implemented new laboratory or classroom activities to engage students with understanding and applying HWE to biological phenomena. Table 2.1 lists several published classroom or laboratory activities designed for teaching HWE. These activities were intended to involve students in meaningful and interesting learning experiences by providing them with non-trivial evolutionary scenarios (Wise, 2018a), employing authentic research data from published journals for solving HWE problems (Bonner et al., 2019; Smith, 2017) or encouraging students to generate their own evidence to test HWE (Christensen, 2000).

Table 2.1. Published activities for teaching Hardy-Weinberg Equilibrium (HWE)

Activity	Author(s)	Year	Course level	Data sources used for solving HWE problems	Activity objectives and highlights
Clam spawning & red tide: Helping students learn the Hardy-Weinberg Equilibrium	Bonner, Piechnik, Kovacs, Warwick & White	2019	Introductory- and senior-level undergraduate biology courses	1. Simulation with colored beads to represent different alleles. 2. Authentic research data published in a journal.	In “hands-on” activities, students use beads for simulation and calculation. Simulation results are validated with authentic research data to provide a meaningful learning experience. The lesson provides detailed disciplinary knowledge as background.
How to teach the Hardy-Weinberg Principle using engaging, non-trivial evolutionary scenarios	Wise	2018	Introductory undergraduate biology course	Fabricated numbers	Provides a four-step guide for teaching HWE, together with six evolutionary scenarios in which students apply the HWE. The complex scenarios are intended to benefit student’s quantitative reasoning and higher-order cognitive skills.
Teaching the Hardy-Weinberg Equilibrium: A 5E lesson plan	Smith	2017	High school biology, AP biology and introductory undergraduate biology course, with students who had some prior modeling experience	1. Simulation with colored paper clips to represent different alleles. 2. Authentic research data published in a journal.	The focus is on student’s understanding of the “big ideas” about the HWE and evolution. The lesson provides students with disciplinary knowledge of the HWE, a research problem, and authentic data from published papers.
Development and assessment of modules to integrate quantitative skills in introductory biology courses	Hoffman, Leupen, Dowell, Kephart & Leips	2016	Introductory undergraduate biology course	Simulation with red and white kidney beans to represent the genotypes in a population of rabbits.	Learning goals include demonstrating quantitative numeracy, interpreting data sets, communicating the interpretations with visual tools, making statistical inferences from data sets, and explaining how evolutionary mechanisms contribute to change in gene frequencies in populations. Using a hypothetical recessive trait, no disciplinary knowledge is provided about the target trait or gene.

Table 2.1. continued

Activity	Author(s)	Year	Course level	Data sources used for solving HWE problems	Activity objectives and highlights
Teaching evolution through the Hardy-Weinberg Principle: A real-time, active-learning exercise using classroom response devices	Brewer & Gardner	2013	Nonmajors undergraduate biology course	Simulation with colored papers to represent different alleles.	The focus is on improving student's conceptual understanding especially about the violations of HWE. No disciplinary context knowledge is provided about the target trait or gene.
Cats as an aid to teaching genetics	Christensen	2000	One-semester course consists of sophomores and juniors who have biology background	Students use a handout to determine the genotype at seven unlinked loci of at least one cat. Instructor collected students' data and used it to illustrate HWE.	This activity reinforces students' conceptual understanding, allows the students to look at population genetics in a very positive light and provides concrete examples of some misunderstood principles. However, using cat as a research subject raised questions about the detailed genetic disciplinary knowledge that determines the phenotype of cats. It is challenging to connect single genes to the observed phenotypes in the cat population.

Although varied in learning objectives, the activities listed in Table 2.1 were intended to shift the teaching of HWE from a traditional focus on calculating with HWE equations to understanding the biological phenomena underlying the HWE. These activities are intended to improve learning about HWE through scientific investigations by actively engaging students. For example, in some hands-on activities, students participated in modeling HWE using colored beads or papers and calculated frequencies of alleles, genotypes and phenotypes to simulate changes in allele frequencies within a population (Bonner et al., 2019; Brewer & Gardner, 2013; Hoffman et al., 2016; Smith, 2017). A cat population activity (Christensen, 2000) is based on the data that students collected as evidence to test HWE. However, using the cat as a research subject raises questions about the detailed genetic disciplinary knowledge that determines the phenotype of cats. Besides, none of the activities in Table 2.1 for teaching HWE provide an opportunity for students to think about the quality of scientific evidence, a practice they would need to understand and use for an authentic scientific investigation. Although some published activities or exercises report hypothesis testing as one of the learning outcomes, there is a lack of detail about the evidentiary reasoning of relevance to formulating or testing hypotheses. Even published activities that have students compare simulation results with authentic research data are simplified. Students need opportunities to engage in experimental design that involves discussions of sampling procedures and research methods, as well as learning about evidence in terms of the nature, scope and quality of evidence to develop their evidentiary reasoning ability.

2.4.2 A HWE laboratory investigation of dog populations

Here we present a novel HWE laboratory investigation of dog populations for undergraduate biology students with scaffolding questions for a practical laboratory lesson and an assessment. The instructional material was informed by the CADE framework to give students opportunities to reason with and about scientific evidence. The HWE laboratory investigation was implemented in an introductory biology laboratory course session, which lasted three hours. Students in this course had to take a biology lecture course as a pre- or co-requisite where they had previously studied and been examined on their understanding of HWE. Before the laboratory session, a 50-minute pre-lab lecture was delivered by a guest professor to review HWE and to introduce color variation in dogs associated with *Tyrosinase Related Protein 1* (*TYRP1*) alleles (Figure 2.2) and variation in the type of dog facial fur related to *R-spondin 2* (*RSPO2*) alleles (Figure 2.3). For their

HWE laboratory investigation, students used Petfinder.com as a data source, they planned how to collect data and they generated evidence to investigate the allele frequencies in the dog populations. The assessment was designed to measure their reasoning with and about scientific evidence for HWE on the final exam at the end of the semester.

Figure 2.2. Comparison of the "black" and "brown" color phenotypes in dog populations caused by the variation in *Tyrosinase Related Protein 1* (*TYRP1*) alleles. Dogs with the "brown" color trait, caused by the variation in *Tyrosinase Related Protein 1* (*TYRP1*) alleles, are in photos marked with green check marks to illustrate the "brown" color phenotype (symbolized by *b*/*b*). It is caused by the combination of two mutations of *TYRP1* and shows up as no black color on nose, paw pads, eye rims or lips. The photos marked with red cross illustrate the "black" color phenotype (symbolized by *B/_*). The two photos in the lower right corner demonstrate how a genetically black (*B*/_) nose can fade over time. This should not be mistaken for a brown nose (*b*/*b*) as the dog remains genetically "black" despite the fading.

Figure 2.3 Comparison of the scruffy face and smooth face phenotypes in dog populations related to variation in *R-spondin 2* (*RSPO2*) alleles. The dogs with scruffy face phenotypes (symbolized by *F/_*) related to *R-spondin 2* (*RSPO2*) are in photos marked with green check marks. *Roof Plate-Specific Spondin-2* (*RSPO2*) encodes an extracellular matrix signaling pathway protein. The dog photo marked with a red cross shows the recessive smooth face phenotype (symbolized by *f/f*). The two photos in the lower right are of the same dog, with a groomed face and with an ungroomed face. These are shown as an example of how the appearance of scruffy face can be altered with regular grooming.

Informed by the CADE framework (Column 2 in Table 2.2), this HWE laboratory investigation was designed to engage students in designing a research study, during which students addressed a novel HWE problem, developed methodology for sampling, independently generated authentic data as evidence, and drew conclusions from their analysis. It not only involved them in practicing hypothesis testing, but, more importantly, the intention was to inspire students to think and reason with and about scientific evidence with scaffolding questions focused on both epistemic and disciplinary aspects before, during, and after the investigation. Students could compare data they collect from the Petfinder.com with the data of the New York City to answer a research question about whether there is a statistical difference in the allele frequencies for *TYRP1* or *RSPO2* between two cities, for example New York City and their hometown, or they could have decided whether there is difference in allele frequencies for *TYRP1* or *RSPO2* over time, for example before and after the Covid-19 pandemic in the New York City.

Box 2.1. A Dog Population Investigation

Consider two phenotypes for which the genetic mechanisms in dogs are known: the black color trait is related to variation in *Tyrosinase Related Protein 1* (*TYRP1*) alleles and a trait for the type of dog facial fur is related to *R-spondin 2* (*RSPO2*). The combination of two mutations of *TYRP1*, symbolized by *b*/*b*, alters eumelanin from black to brown and gives dog fur and skin the "brown" phenotype, which shows up as no black color on nose, paw pads, eye rims or lips (Figure 2.2). The "black" phenotype is due to the dominant allele and can be symbolized by *B*/_ (Dreger et al., 2019; Jancuskova et al., 2018; Schmutz & Berryere, 2007; Schmutz et al., 2002). Scruffy fur phenotype on a dog's face is related to *Roof Plate-Specific Spondin-2* (*RSPO2*), which encodes an extracellular matrix signaling pathway protein. The *RSPO2* allele for the scruffy trait is due to the dominant allele, illustrated by *F*/_, in contrast to smooth facial fur on dogs that are homozygous recessive for this trait, illustrated by *f*/*f* (Figure 2.3) (Cadieu et al., 2009; Dreger et al., 2019).

A website that lists adoptable animals across most of North America is http://PetFinder.com. Using Petfinder.com, a scientist of canine genetics found that in New York City the gene pool for adoptable dogs is mostly smooth faced (a recessive trait only seen in dogs that inherit two copies of the *RSPO2* gene for smooth face). But many dogs carry the *TYRP1* gene mutation that causes some dogs to be missing black pigmentation. On February 1, 2019, in New York City, the counts of *RSPO2* and *TYRP1* phenotypes were as follows:

Smooth Black	**Smooth Brown**	**Scruffy Black**	**Scruffy Brown**
f/*f B*/_	*f*/*f b*/*b*	*F*/_ *B*/_	*F*/_ *b*/*b*
80	22	15	1

Assuming Hardy-Weinberg Equilibrium:

- q^2 = frequency of the recessive phenotype
- q = frequency of the recessive allele
- p = frequency of the dominant allele → p = 1 – q
- For *TYRP1* brown:
  - q = *b* = brown = 0.442
  - p = *B* = black = 0.558
- For *RSPO2* scruffy:
  - q = *f* = smooth face = 0.9302
  - p = *F* = scruffy face = 0.070

What research question can be investigated with this and other data from http://PetFinder.com**?**

Table 2.2. Scaffolding questions informed by the Conceptual Analysis of Disciplinary Evidence (CADE) framework for the dog population investigation discussions

Stage	Align with the CADE framework	Instructional practice	Scaffolding question
Before the Investigation: Reasoning with and about the HWE model to prepare for the investigation.	**Theory => Evidence Relationships** Model Articulation: Formulate/test hypotheses or pose explanations and a rationale for the investigation	A pre-laboratory lecture helps students understand the Hardy-Weinberg Equilibrium (HWE) Model and the canine genetics related to the dog population investigation. The instructor guides the student investigators to apply the HWE model to a dog population using the dog data from New York City as a worked example with dog populations to benefit investigators who lack experience with applying math to biological problems, who lack motivation to solve problems, or who lack contextualized knowledge about how to apply the Hardy-Weinberg Equilibrium model. During the lab session, the instructor guides students to revisit disciplinary knowledge about the HWE and canine genetics. With guidance the class poses a research question they will answer. For example, students may want to find out if there has been a change in allele frequencies of TYRP1 and/or RSPO2 for New York City dogs over time or they might be curious about whether dogs in their hometown differ from the New York dogs. The scaffolding questions highlight both disciplinary knowledge and epistemic considerations to think and reason about the HWE model and their rationale for their research question to generate testable hypotheses for a strong investigation.	**Disciplinary Knowledge** • Why do biologists care about the HWE model? Why use it for an investigation? • How do the assumptions for Mendelian genetics differ from those for populations with HWE? • What would a biologist think count as evidence and what sort of data are collected according to HWE? • Pose a research question to be answered about a population and state the null hypothesis. **Epistemic Considerations** • Considering the various models, which is most appropriate to address your research question and why? • What limitations are associated with the model?

Table 2.2. continued

Stage	Align with the CADE framework	Instructional practice	Scaffolding question
During the Investigation: Sample the dog phenotype data from the Petfinder.com and testing of Hardy-Weinberg Equilibrium or comparing two populations with Chi square test.	**Evidence <=> Data Relationships** Designing, executing, analyzing evidence from investigations	The instructor leads a discussion for student investigators to develop a non-biased sampling strategy. Using Petfinder.com the student investigators apply and refine a sampling strategy to collect data, they design a data table to compile all the findings and they discuss how to use the data as evidence to answer their research question. The investigators ca apply chi-square test with the “expected versus observed” counts data (HWE) or to compare two conditions (dogs in California versus New York, for example). With scaffolding questions from both disciplinary knowledge and epistemic considerations, the instructor can prompt students to think and reason with the data including the collection and analysis procedures to consider the scope and quality of the evidence they generate.	**Disciplinary Knowledge** • How is the data used as evidence for testing your model? • What statistical analysis models are used to organize/compare data to see whether or not a population is in Hardy-Weinberg Equilibrium? • Given the HWE assumptions, what are the known sources of error and how will they be accounted for? • Why did you set this specific alpha-level for the statistical test? Would other levels be appropriate? • What analysis models are used to compare data? **Epistemic Considerations** • Are the technical data collection procedures adequate? • Considering the sampling procedures, are data sampled in an unbiased way that is representative of the population? • What do you think of the quality of your data for answering the research question? • What additional evidence would give more confidence?

Table 2.2. continued

Stage	Align with the CADE framework	Instructional practice	Scaffolding question
After the Investigation: Interpret the evidence and draw the conclusion.	**Evidence => Theory Relationships** Models of argument: Sufficiency of conclusions	Student investigators describe the populations they are comparing assuming each is in HWE, and they consider limitations of this assumption in drawing conclusion from the evidence they generated from their investigation when the instructor leads a discussion about the interpretation of the results. The scaffolding questions consider both disciplinary knowledge and epistemic considerations to prompt students' thinking and reasoning about the strength of their evidence interpretation and the sufficiency of their conclusion or claims.	**Disciplinary Knowledge** • What has been learned about the population from the evidence? • When performing the proposed hypothesis test, what does it mean if you fail to reject your null hypothesis? • Are the findings consistent with the idea that the population evolved? • What would a biologist think could be a likely explanation for the findings? **Epistemic Considerations** • How confident are you in this interpretation? • How confident are you that H_0 should have been rejected/not rejected? • Are there any alternative interpretations to explain the findings? • Do the findings fit with other reports from published studies?

Instructors can apply the scaffolding questions at various parts of the lesson plan (Table 2.2) to prompt deeper thinking and reasoning with and about scientific evidence while guiding students through the investigation. These scaffolding questions involve figuring out how to investigate if the allele frequencies of a Mendelian trait in an observed population differ from a comparison population in a different place or the same population at a different time, using the gene frequency as evidence for evolution. For example, before the investigation, the instructor can use the question "What important unsolved problem could be addressed with HWE in your investigation" (Theory => Evidence relationships, Disciplinary knowledge) to prompt discussion of a research questions that they could investigate. Note that the Disciplinary knowledge component in Table 2.2 recognizes specific disciplinary considerations to inform the investigation, such as HWE, Mendelian genetics, and relevant statistical models. In contrast, the Epistemic considerations in Table 2.2 raise questions about the nature, scope and quality of scientific evidence to support epistemic reasoning about evidence with more generalized strategies.

Box 2.2. A dog population investigation assessment

According to "Dogs", a series on Netflix, *Territorio de Zaguates* is a free-range shelter run by people who are dedicated to saving dogs abandoned in Costa Rica. The phenotypic traits in the shelter were well analyzed. The head vet of the shelter stated that these dogs are unique at Costa Rica.

For comparison, a scientist of canine genetics, found that the gene pool for adoptable dogs is mostly smooth faced (a recessive trait only seen in those that inherit two copies of the *RSPO2* gene for smooth face), but many dogs carry the *TYRP1* gene mutation that causes some dogs to be missing black pigmentation. Using a website that lists adoptable animals across most of North America is http://PetFinder.com these counts of *RSPO2* and *TYRP1* phenotypes were found on February 1, 2019, in New York City:

Smooth Black	Smooth Brown	Scruffy Black	Scruffy Brown
f/f B/_	*f/f b/b*	*F/_ B/_*	*F/_ b/b*
80	22	15	1

Questions

1. What would you observe about the dogs in the Netflix show, *Territorio de Zaguates*. to find out if those dogs are really different from dogs that are up for adoption in New York City? Is there evidence that the gene pool for these dogs is different in Costa Rica? Explain an approach to doing research on the dogs. What should the investigators be looking at to determine their uniqueness? Why would these observations be interesting and/or important?
2. The vet has described the phenotypes of 1000 dogs at the *Territorio de Zaguates* free-range shelter. What types and how many dogs with each phenotype would you expect to find in this data if the population does NOT differ in terms of the allele frequency for the traits this scientist reported for adoptable pets in New York City? Assume both populations are in Hardy-Weinberg Equilibrium.
3. Given what you know about Mendel and the Hardy Weinberg Equilibrium principle, what questions do you have and what additional evidence would help you figure out what is happening with the abandoned dogs in Costa Rica?
4. What else might you need to know to improve the quality and the accuracy of the vet's claim that the abandoned dogs in Costa Rica are unique?

The assessment in Box 2.2 presents open-ended questions that include and go beyond simple calculation with HWE equations. These questions are designed to reveal students' thinking about the entire investigation process in terms of both disciplinary knowledge and epistemic considerations. For example, the question "Given what you know about Mendel and the Hardy Weinberg Equilibrium principle, what questions do you have?" is aligned with the Theory =>

Evidence relationship. Student reasoning about Evidence <=> Data relationships is revealed when they consider "*What additional evidence would help you figure out what is happening with the abandoned dogs in Costa Rica*?", and the question "*What else might you need to know to improve the quality and the accuracy of the vet's claim that the abandoned dogs in Costa Rica are unique?*" is related to the Evidence =>Theory relationships. The assessment was designed to reveal students' understanding of the HWE model, their competence with hypothesis testing and their reasoning about the nature, scope, and quality of the data that underpin their use of scientific evidence. In summary, this novel HWE laboratory investigation, the scaffolding questions and the assessment provide opportunities to engage students in authentic research in order to develop their competence with research design, hypothesis testing, and reasoning.

2.5 The Implementation of the CADE Framework: Laboratory Discussions from an Introductory Biology Laboratory Course

Here we present changes in laboratory discussions before and after we implemented the HWE laboratory investigation with embedded scaffolding questions to illustrate how the CADE framework influenced the teaching of our HWE laboratory course. Selected teaching staff members were invited to collaborate with the first and the last authors to improve teaching strategies according to the CADE framework by modifying the lesson plan for the HWE laboratory investigation between semesters. The modified lesson plans were implemented each semester from spring 2018 to spring 2019 semesters. We tracked the changes in the laboratory discussions led by participant instructors by videotaping the laboratory instruction from the baseline course in spring semester 2018 and two continuous iterations for implementation the CADE framework in fall 2018 and spring 2019 semesters. In order to indicate what aspects of evidentiary reasoning had been discussed during the HWE laboratory investigation and what were still missing, the laboratory discussions were transcribed and instructional questions were coded with the three relationships and the two components of the CADE framework. Two independent coders worked on 25% of the transcripts to get the agreement on the codes at the beginning of the coding process. Then one of the coders coded the rest of the transcripts.

One of the participant instructors was an undergraduate teaching intern who participated in all three semesters. She earned a bachelor's degree in biochemistry in 2019 while completing minors in both Statistics and Biotechnology with a perfect 4.0 GPA. During her undergraduate career, she also participated as an investigator in several research projects. She had been teaching the same laboratory course for one semester even before volunteering to participate in our HWE laboratory improvements. Her excellent academic performance and the experience of teaching and research were aligned with her quick ability to understand and apply the CADE framework while helping to devise scaffolding prompts to modify the HWE laboratory lesson plan during each iteration. Next, her laboratory instructions are used as examples to illustrate the changes made to instructional questions and prompts based on the CADE framework for guiding students' thinking and reasoning about scientific evidence during the HWE laboratory investigation. The scaffolding questions used in the lab are presented in Appendix B.

The participant instructors who contributed to course improvements were paid for their participation. As their laboratory discussions were recorded, the laboratory instructor and student participants agreed to participate according to a protocol that was reviewed and approved by the Institutional Review Board (IRB#1702018760251).

2.5.1 The baseline course

During the baseline HWE activity, students were given phenotype numbers to calculate both allele frequencies and genotype frequencies (Figure 2.4). Alignment with the CADE framework revealed that questions and prompts used by the volunteer instructor through the baseline activity only covered two relationships in the CADE framework, which are the Theory => Evidence and Evidence <=> Data, and even in these two relationships, some important components were missing. Most of the questions in the Theory => Evidence relationships were intended to refresh students' memory about the HWE assumptions. For instance, the instructor said, "… *the population has to be very large. Can anybody give any predictions about why that might be?*" (Theory => Evidence relationships, Disciplinary knowledge). Students then discussed that allele frequencies in the large population would unlikely be affected by random events since one individual makes up a lot less of a large population. There were no questions to prompt discussion about a key domain phenomenon: that the appropriate model is HWE and not just Mendel's Laws applied to population genetics. No questions were implemented to guide students to compare the two genetic models they had learned, or to discuss how Mendel's Laws or HWE fit different types of investigations. This led to the result that some students failed to select the proper model to address their population genetics study. In the final written exam of the spring semester 2018, over one third of the students, applied Mendel's Laws and used Punnett squares to calculate the genotype frequencies in solving a population genetics problem, instead of considering p or q as allele frequencies (unpublished data).

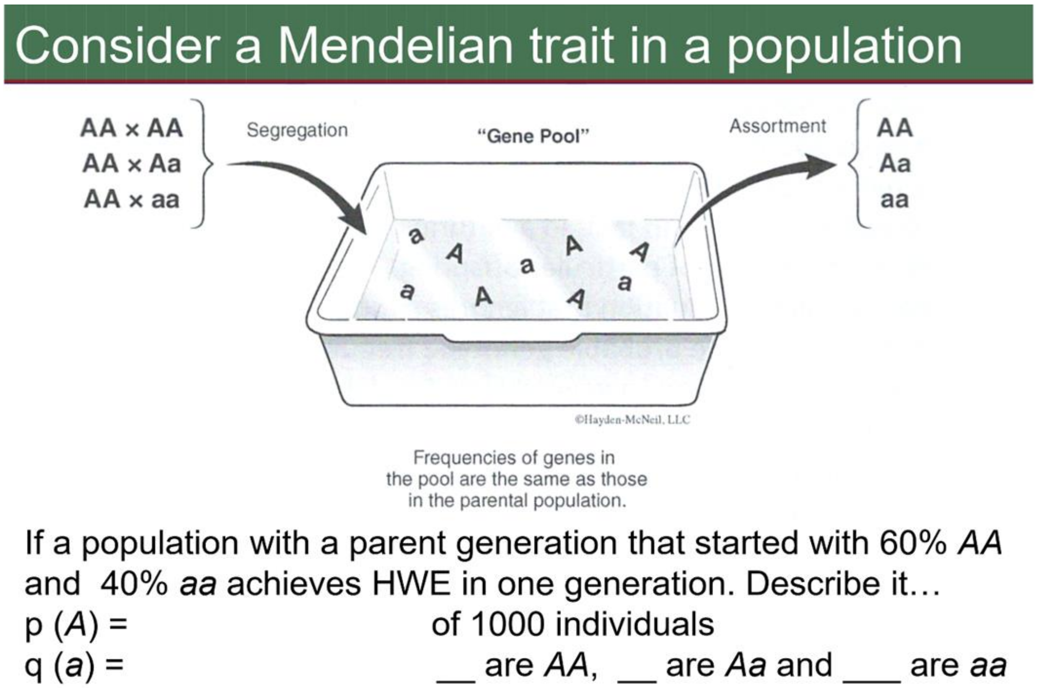

Figure 2.4. The Hardy-Weinberg equilibrium (HWE) laboratory activity in the baseline course. This HWE laboratory activity illustrated the allele frequencies in the gene pool and focused on helping students calculate with the HWE equation using numbers of genotype frequencies of a trait that were given to students.

Since the activity in the baseline course focused on applying HWE in terms of an equation with a given set of numbers, most of the guiding questions in the Evidence <=> Data relationships were simply about how to calculate the allele or genotype frequencies with given numbers. For instance, the instructor asked "… *so if you have 40% aa and then 60% of AA, what would the proportion of just the A allele be in the population?*" (Evidence <=> Data relationships, Disciplinary knowledge). With the given numbers, there was no opportunity for students to discuss and critique the sampling methods, or the accuracy of the methods and techniques used to gather the data.

Most of the questions in the baseline course were intended to prompt students' thinking about disciplinary knowledge related to the HWE activities. There were no guiding questions to prompt students' epistemic considerations about the quality or reliability of evidence used in the activity. This illustrates the need to modify the lesson and the scaffolding questions to prompt students' epistemic considerations during their HWE laboratory investigation to encourage students to think about the nature, scope and quality of the evidence used during the investigation.

2.5.2 Laboratory discussions during the dog population investigation

After implementing the dog population investigation and incorporating scaffolding questions into the lesson plan for teaching HWE, several major changes were observed in the laboratory discussions when students were talking about scientific evidence during the investigation, the comparison of instruction differences are presented in Table 2.3. First, more discussions guided by the instructor about scientific evidence were categorized into the first three relationships in the CADE framework. This indicates that students thought and talked about multiple aspects of scientific evidence during the dog population investigation. These guided discussions covered important components for evidentiary reasoning that were missing from the baseline laboratory instruction. For example, in order to help students compare Mendel's Laws to the HWE and to choose the proper model for the investigation, the instructor said, "*We have learned about two genetic models - Mendelian genetics and population genetics with Hardy Weinberg Equilibrium. What are the assumptions for both of them?* (Theory => Evidence relationships, Disciplinary knowledge). *Can you use either model? Which one is more appropriate and why?*" (Theory => Evidence relationships, Epistemic considerations). These questions led the students compare the two genetics models they had learned and to think about the relevant model and mechanisms underlying changes of allele frequencies in a dog population.

Table 2.3. Counted differences in the lab instruction between the baseline course and the dog population investigation

Constructs and Practices	Baseline		Dog population investigation	
	Disciplinary knowledge	Epistemic considerations	Disciplinary knowledge	Epistemic considerations
Theory => Evidence relationships	9	0	15	2
Evidence <=> Data relationships	12	0	16	7
Evidence => Theory relationships	1	0	13	9
Total	22	9	44	18

The features of the dog population investigation encouraged students to participate in the entire hypothesis testing process, thus providing a context for the instructor to implement the CADE framework with scaffolding questions to inspire students' evidentiary reasoning during the process. The students identified a research question, generated hypotheses, collected and interpreted data as evidence and drew conclusions. For example, before the investigation, the instructor asked "*… so, what research question are you interested in? Do you have any hypotheses on whether or not you expect your allele frequencies to be similar or different than in New York?*" (Theory => Evidence relationship, Disciplinary knowledge). One student mentioned that his hometown in a rural area of North Carolina is prone to flooding. He wondered whether the fur type of the dog which related to *R-spondin 2* (*RSPO2*) in his hometown would differ from a bigger city, like New York City, that is not rural or so prone to flooding. The class was interested in this research question and decided to investigate whether there were statistically significant differences in allele frequencies of smooth face fur (*f/f*) between a rural location in the North Carolina flood zone and New York City. During the investigation, the instructor led discussions about evaluating the sampling methods and details of the statistical methods applied to analyze the data. This let the whole class discuss how to process an unbiased sampling method, for example, how many dogs each of them would count and how they could avoid counting the same dog twice on Petfinder.com as evidence. After processing the data to generate evidence, the instructor asked, "*So what conclusions can you draw?*" and then "*So, we've rejected our null hypothesis, now what do we say about our model and our data?*" (Evidence => Theory relationships, Disciplinary knowledge). The whole class used evidence to draw their conclusion based on the evidence to claim, there was no significant statistical difference between dog populations in rural location in the North Carolina and New York City. They then discussed potential reasons and alternative interpretations for this conclusion.

Another change was that with the implementation of scaffolding questions of epistemic considerations, students started to talk about the limitations and evaluations of the theory and evidence of relevance to the dog population investigation (Table 2.3). The instructor guided students to think about the limitations of the theory by asking "… *but any other limitations that you might think of for this sort of model …?*" (Theory => Evidence relationships, Epistemic considerations). The class discussed the scope and quality of the evidence collected by students and used during the investigation when the instructor asked, "*How much confidence do you guys have in this evidence for allele frequencies? So, does anybody have any ways and ideas of how you might want to increase your confidence in this data?*" (Evidence <=> Data relationships, Epistemic considerations). These changes support the idea that implementation of the CADE framework can help an instructor use scaffolding questions that cover epistemological aspects of evidentiary reasoning to guide student's thinking and reasoning with scientific evidence in a way that is integrated into the disciplinary context of their HWE laboratory investigation.

2.6 Discussion

In this report, we presented the CADE framework in the context of a HWE laboratory investigation (Table 2.2) and illustrated how the implementation of the CADE framework influenced the laboratory discussions guided by one instructor during the investigation. The CADE framework targets known difficulties with students' evidentiary reasoning during investigations by giving them the opportunity to blend deep disciplinary knowledge and investigative practices with the epistemic considerations that are key to evidentiary reasoning. And also explicitly drawing instructors' attention to the distinction between the disciplinary knowledge and epistemic considerations of evidentiary reasoning and how to prompt for each can promote students' deeper thinking during the investigation (Samarapungavan, 2018). The scaffolding questions listed in Table 2.2 cover both aspects of disciplinary specificity and epistemic generality for three relationships to consider: Theory => Evidence refers to the use of relevant disciplinary knowledge to inform what counts as evidence for a particular area of study, and what sort of data to collect; Evidence <=> Data recognizes the need for disciplinary knowledge to inform the isolation and definition of variables for a particular research design, procedures such as appropriate sampling and measurement, as well as the precision and accuracy of techniques and equipment to be used in order to optimize the reliability of the evidence; Evidence => Theory involves the disciplinary knowledge implicit to the tracking and quantifying of known sources of error, alternate interpretations that could be evaluated, limitations and uncertainties to be explicitly addressed, and whether findings are consistent with disciplinary knowledge or raise questions about the ideas from previous studies that inform the investigation. Such details do not all need to be given in laboratory protocols if the laboratory investigation provides opportunities to engage the students with discussions of these practices.

Guided by the CADE framework, the dog population investigation highlights engaging students with evidentiary reasoning in their investigating process. This laboratory investigation uses a common pet as the subject to investigate, which may effectively engage students in the HWE laboratory investigation since many students love dogs. It calls on detailed disciplinary knowledge by providing students with information about the exact genes that control the phenotypes they can investigate, including *TYRP1* and *RSPO2* allele variants. By doing this, students have an opportunity to connect disciplinary knowledge for their study to a detailed context that calls on their personal knowledge and experience, which is an essential component for development of evidentiary reasoning according to the CADE framework. After learning about *TYRP1* and *RSPO2* allele variants, most students can describe the relevant phenotypes and predict the genotype of a dog they know best which allow students to focus on both the theory and scientific evidence underlying the HWE laboratory investigation. The dog population investigation provides opportunities for students to practice hypothesis testing during this process they gather and use evidence. By discussing and answering the scaffolding questions in Table 2.2, students reason with and about evidence from the disciplinary and epistemic perspectives. The guided discussions about what variables are important for their research, how to collect data as evidence, what sampling strategies to use, and what conclusion(s) to draw from the evidence for the investigation, are intended to help students practice thinking about the nature, scope and quality of the evidence. From the teaching perspective, the embedded scaffolding questions presented in Table 2.2 are ready to apply for guiding students' evidentiary reasoning. Unlike other HWE activities that use colored buttons, beads, or other manipulatives, the dog population investigation uses Petfinder.com, which is low cost and easily access for implementation and thus provides a potential online laboratory teaching format for including authentic research.

HWE is a fundamental model that plays an essential role for understanding evolution in undergraduate biology education. Due to the abstract nature and mathematical background of HWE, students who mainly perform calculations with the HWE equation may not actually understand the biological phenomena underlying their investigations (Wise, 2018b). Because of the importance as well as the challenges for teaching and learning HWE, educational researchers and instructors have been designing and implementing activities that aim to facilitate students' understanding and applying of the HWE in authentic and engaging ways (Bonner et al., 2019; Brewer & Gardner, 2013; Smith 2017; Wise, 2018b). However, there is room for improvements that could engage students in thinking and reasoning with and about scientific evidence during their HWE laboratory investigations. Research with the CADE framework could guide modification of other types of HWE laboratory investigations, for instance the activities mentioned in Table 2.1 could be modified to give students more opportunities to practice reasoning about multiple aspects of scientific evidence. Modifications to a laboratory activity can be informed by the CADE framework to expand the activities from use of the Chi-square test to compare expected and observed allele frequencies in a population between different generations or in different places, by also giving students the opportunity to explore both disciplinary and epistemic components to evidence for changes in a population that could be attributed to natural selection or genetic drift.

Others have reported that instructors' questions can engage and guide students through investigations by eliciting and scaffolding students' thinking if the instructors actually lead the discussions about observations, assumptions and reasoning (Kawalkar & Vijapurkar, 2013). However, in an undergraduate laboratory where instruction is typically managed by graduate and undergraduate teaching staff who get very little pedagogical training, it can be challenging to get staff to help students discuss the evidence rather than just telling students what to do (Gardner & Jones, 2011; Luft et al., 2004; Sundberg et al., 2005). Our findings show that after implementing the CADE framework to modify the lesson plan and the laboratory instruction, a participant instructor used more questions related to multiple aspects of evidentiary reasoning for guiding her students through the HWE laboratory investigation. This indicates that the instructor was able to lead students to think and reason more about the scientific evidence throughout the process of scientific investigation. The CADE framework also helped the instructor notice the importance of epistemic considerations in evidentiary reasoning. The instructor began to include scaffolding questions that prompted students to think and reason about the limitations and the nature, scope and quality of the evidence. The reasons for these interesting changes include the improvement in the laboratory task, but also, importantly, that the CADE framework helped unpack the complexity of evidentiary reasoning into questions that are related to essential components of evidentiary reasoning throughout the process of authentic research.

2.7 Limitations and Directions for Future Research

Several limitations to this study should be addressed. First, the participant instructor we observed was more excellent than typical laboratory instructors in both academic performance as well as in research and teaching experience and her laboratory instruction showed deep understanding of the CADE framework. There is an additional need to explore professional development approaches for all laboratory instructors. With the CADE framework as an introduction to components of evidentiary reasoning and by providing both good and poor example discussions of evidentiary reasoning, it may be possible to help all laboratory instructors implement the CADE framework to guide discussions throughout their particular laboratory investigations. With the dynamic and interactive features of scaffolding, the goal of including evidentiary reasoning discussion could become more feasible. Research is also needed to examine how and in what conditions the CADE framework should inform scaffolding questions to cultivate a learning environment and laboratory classroom atmosphere where students will become adept at thinking and reasoning with scientific evidence autonomously during their scientific investigations. By addressing these limitations, the development of evidentiary reasoning ability could benefit not only students' academic performance and science career preparation, but also strengthen their decision-making skills in everyday life, which is an important target for 21st century laboratory instructions.

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CHAPTER 3. IMPLEMENTING THE CONCEPTUAL ANALYSIS OF DISCIPLINARY EVIDENCE (CADE) FRAMEWORK IN THE INSTRUCTION OF A STRUCTURAL BIOLOGY LAB INVESTIGATION

3.1 Introduction

3.1.1 Scientific evidence and evidentiary reasoning

Scientific evidence is essential for knowledge construction in science disciplines. Using scientific evidence to compare and assess models with the reality is the major approach how scientists analyze if theories are consistent with the real world (Giere, 2006). Scientific evidence is generated based on the established theories in a discipline. Guided by theories and models, scientists make decisions on what to observe, how to describe observations, and how to share findings with others (Manz, 2016). Scientific evidence is complex and multifaceted, as a result that scientific evidence is constructed with various disciplinary knowledge, as well as evolving methodologies. It is also involved in multiple scientific activities and practices, such as identifying research questions and designing experiments to test hypotheses (Samarapungavan, 2018). Evidentiary reasoning takes place in the entire process of constructing scientific evidence. It is the reasoning with and about scientific evidence during the collection, use and evaluation of scientific evidence in writing claims or supporting inferences (Pellegrino et al., 2014; Samarapungavan, 2018; Wills, 2018).

As science education shifts the focus toward helping students understand the nature of science as well as the process of science, helping students understand and use scientific evidence has been brought to educational researchers' attention for its essential role in science learning and the development of epistemic competencies (Barzilai & Chinn, 2018; McNeill & Berland, 2017). The competence of using and reasoning with scientific evidence was emphasized by many national reports, education reform documents and research studies (e.g. AAAS, 2011; Pelaez et al., 2017). For example, the Vision and Change report emphasized that students need to evaluate the experimental evidence in order to engage in the process of science properly (AAAS, 2011). Engaging students in scientific practices and investigations and helping students understand and use evidence in argumentation steer students' attention in science learning from simple memorization towards developing a more comprehensive understanding of scientific concepts and processes (Takao, Kelly, 2003). Science education should prepare students for writing claims, answering questions and looking for the coordination between theories and evidence using evidentiary reasoning when they engage in the complex process of science investigations (Driver et al., 2000; Manz et al., 2020).

Despite the many efforts that focused on scientific evidence and evidentiary reasoning, research reported that students still had difficulties in understanding and using scientific evidence in the process of writing claims and making argumentations. For example, students often considered evidence as self-evident that it cannot be openly interpreted, neither be constructed (Driver et al., 1996; Manz, 2016; Sandoval & Çam, 2011). Sandoval & Millwood (2005) reported that middle school students often failed to cite sufficient evidence when they wrote explanations in a natural selection investigation. In a previous study, I discovered that undergraduate students experienced difficulties in reasoning with evidence. More than one third of the students failed to refer to the proper theory during a population genetics investigation to test Hardy-Weinberg Equilibrium (unpublished result). As one of the higher-order skills, scientific reasoning may not be developed naturally among most students in a traditional curriculum (Kuhn, 2009). Thus, there is a need to include reasoning with and about evidence as a major learning objective and exploring the influence of instructional methods on developing evidentiary reasoning skills.

Most of the studies on using scientific evidence focused on student's ability to coordinate evidence in writing argumentations and explanations and were based on analyzing the components and structure of a single argumentation (e.g. Kulatunga et al., 2013; Lawson, 2004; Manz, 2016). The evidence construction in the process of scientific investigation has been under evaluated (Duncan et al., 2018; Manz, 2016; Samarapungavan, 2018). These results indicated the need of research in helping students understand and use the scientific evidence in the process of science investigations.

3.1.2 The Conceptual Analysis of Disciplinary Evidence (CADE) framework

The Conceptual Analysis of Disciplinary Evidence (CADE) framework (Samarapungavan, 2018) is employed as the theoretical framework for this study The CADE framework unpacks the scientific evidence into four constructs and practices that are aligned with the process of scientific investigation. These constructs and practices are: the Theory => Evidence relationships, the Evidence <=> Data relationships, the Evidence => Theory relationships and Social Dimensions.

The constructs and practices under the four relationships are interrelated, indicating that scientific evidence is complex and multifaceted, and related to various knowledge and practices of disciplinary theories and methodologies. Because the context for this study is a scientific investigation in an introductory biology lab course, only the first three relationships in the CADE framework, which are the Theory => Evidence relationships, the Evidence <=> Data relationships, the Evidence => Theory relationships, were taken into consideration due to that they represent the process happened in the classroom investigation.

The CADE framework links scientific evidence with disciplinary knowledge and epistemic considerations, which are two major components for understanding and reasoning with and about scientific evidence. Disciplinary knowledge refers to the knowledge of theories, models and disciplinary methodologies that one need to know to properly generate and evaluate evidence. It provides the necessary context for evidentiary reasoning and shapes the judgments about evidentiary reasoning (Samarapungavan, 2018). A student needs to grasp adequate disciplinary knowledge to decide what questions can be answered, what variables are important, what techniques should be applied, and what conclusion can be made from the evidence. For example, in order to perform a homology modeling for predicting protein structures and functions, a student needs to obtain the disciplinary knowledge about homology modeling, the central dogma, protein structure, the relationships between structural and functional similarities, as well as the methodological knowledge on what software and databases should be used to conduct homology modeling. Epistemic considerations are ideas about the nature, scope and quality of the scientific evidence, which also play an essential role in the entire process of evidence generation and evaluation. For example, in the same homology modeling process, a student also needs to evaluate the alternative theories and models, as well as the credibility of methods and tools used. Developing advanced evidentiary reasoning skills requires the understanding of conceptual and procedural knowledge as well as epistemic considerations, which are interrelated with each other in the process of evidence construction (Sandoval & Reiser, 2004).

Because the CADE framework targets the comprehensive understanding of scientific evidence construct and evidentiary reasoning, it was employed as the theoretical framework for exploring instruction on evidentiary reasoning in this study. The CADE framework was implemented in the professional development activities for participants, in designing scaffolding questions for participants to prompt students' thinking and reasoning with evidence during the class investigation, as well as in the data analysis process for revealing components of evidentiary reasoning.

3.1.3 Disciplinary knowledge and general knowledge of evidentiary reasoning

Disciplinary knowledge for scientific reasoning interwinds with theories, empirical research, methodologies and sociology aspects within the discipline, as well as the domain or the topic for a particular scientific inquiry, and it is essential for conducting successful evidentiary reasoning (Clark A. & Ravit, 2018; Samarapungavan, 2018). General knowledge of reasoning refers to "*the knowledge of reasoning strategies and practices that are thought to be generalizable broadly within scientific domains*" (Clark A. & Ravit, 2018), including the understanding and use of general scientific strategies, for example, general hypothesis testing skills and the controlling of variables. Even though the sophisticated scientific reasoning relies on the grasp of disciplinary knowledge, general knowledge has its value in supporting scientific reasoning, including prompting better understanding about scientific issues and making correct judgement about the trustworthiness of reasoning practices (Clark A. & Ravit, 2018). The majority of studies about general knowledge and disciplinary knowledge of reasoning focused on the debate about their influence on student's reasoning ability (e.g. Mcneill & Krajcik, 2006). In this study, the influences of disciplinary knowledge and general knowledge of reasoning on lab instruction were compared and evaluated by developing and implementing two types of scaffolding questions, general evidence scaffolds (GES) and disciplinary evidence scaffolds (DES). The GES refers to questions, hints or prompts that label and draw students' attention to key aspects of evidence but without explicit links to disciplinary knowledge, for example *"In order to confirm your findings, what different tools would be applied to all the variables and in what order"*. The GES helps students think more about the nature and quality of evidence in the context of their learning tasks. In contrast the DES refers to questions, hints or prompts that label and draw students' attention to key aspects of evidence with explicit links to disciplinary knowledge, for example, "*In research that involves the process of protein homology modeling, what online tools would a biologist use and in what order*". Based on assumption/idea that evidentiary reasoning is tightly related to the disciplinary context, this study aims to explore how GES and DES questions would influence instructors in leading the discussions on evidentiary reasoning during classroom investigations.

3.1.4 Graduate teaching assistants (GTAs) in undergraduate biology lab courses

Participants in this study are graduate teaching assistants (GTAs). GTAs are usually the majority instructors in undergraduate biology lab courses and thus play an important role in undergraduate biology education (Rushin et al., 1997; Sundberg et al., 2005). GTAs have more opportunities to deliver one-on-one instruction to students in a lab course section, compared to an instructor who faces hundreds of students in a lecture course. Thus, instructional behaviors and performance of GTAs, for example, the pace of instruction and their questioning strategies, could significantly impact student learning experiences and achievements in a course, and as a result, will have long-term effects on students retention rate in the science, technology, engineering and math (STEM) areas (Huffmyer & Lemus, 2019; Jaeger, 2008).

The shift of learning biology through scientific investigation provides both opportunities and challenges for GTAs. It was reported that GTAs benefited from the experience of teaching and mentoring research at the undergraduate level, especially in the inquiry-based courses and Course-based Undergraduate Research Experiences (CUREs), with the improvement in the ability to explain the process of science, generate hypothesis, and design experiments for their own research projects (Heim & Holt, 2019, Feldon et al., 2011). Besides these benefits on both teaching and research, GTAs also face several challenges, including time management between their own research and preparing for teaching, and feeling under-prepared for guiding the inquiry and research with the traditional teaching assistant training (Heim & Holt, 2019). Because of GTA's important role in undergraduate biology education and the challenges they face with teaching, more efforts are needed to prepare GTAs' teaching of scientific inquiry and investigation. These preparations should be focused on the necessary content knowledge and pedagogical skills, in addition to logistics and classroom management.

In this study, two GTAs were invited to a series of professional development with the CADE framework. They designed and implemented scaffolding questions as interventions to facilitate students' evidentiary reasoning as they guided the structural biology lab investigation in an introductory biology lab course. Recording of the lab instruction and interviews of GTAs were conducted to get a better understanding of the GTAs' experiences about the CADE framework implementation. This study provided some implications on how to support instructors and GTAs in teaching evidentiary reasoning in undergraduate biology lab courses.

3.2 Research Questions

To get the in depth understanding of GTAs' experience of integrating evidentiary reasoning in their instruction in a structural biology module of an introductory undergraduate biology lab course, this study aims to answer the following research questions:

1. How did the two GTAs lead the discussions on evidentiary reasoning guided by the CADE framework during the structural biology investigation?
2. How did GES and DES influence the GTAs' instruction during the structural biology investigation?

3.3 Methods

A qualitative multi-case study (Meyer, 2001, Yin, 2002) was conducted to answer the research questions and explore how the two participating GTAs implemented the CADE framework into their lab instruction. Each GTA's experience served as a case. Data from lab instruction and interviews were collected and analyzed, which allowed the intensive comparisons between the two cases.

3.3.1 Study context: A structural biology module

The study was conducted during the spring semester of 2020. The context of this study is a structural biology module which is one of the four modules in an introductory level biology laboratory course at an American research-intensive institution in the Midwest. The laboratory course is required for all biology major students and was designed informing by literatures on CUREs. The discipline of structural biology and bioinformatics tools have gained importance among biological scientists. The ability to search and acquire information from online databases become an indispensable competence for scientists in many biology related disciplines. Providing evidence-based structural biology projects to students in the introductory level biology courses helps students grasp the conceptual and methodological knowledge in structural biology that can be useful in their upper-level courses or in their own research projects (Brown, 2016). Moreover, students can appreciate the complexity of scientific evidence that scientific evidence can be obtained not only from the experimental methods, but also from computation and simulation.

The structural biology module lasted for four weeks. A junior structural biology professor had recently worked with a graduate student to incorporate a structural biology module into the introductory biology lab course. According to the professor, this module aimed to help students understand the relationship between sequence, structure and function of complex macromolecules including DNA and proteins. Through the module, students could learn about the content knowledge in structural biology, including the four levels of protein structure, the central dogma, and the relationship between sequence and function of macromolecules, as well as get familiar with some online software and databases that are used in structural biology research. This module services as a starting point for freshmen to understand and get interested in the structural biology discipline.

Two classroom projects were provided to students at the beginning of the module for investigating two function-unknown proteins. One protein has been found in a type of thermophilic bacteria exists in the hot springs of Yellowstone National Park and the other was from a new psychrophilic yeast which was isolated from the ice in Antarctica. Students worked in groups of three people, as one of them worked as the primary investigator (PI), and chose one project that they were interested in. During the four weeks of the structural biology module, each group generated a research question, formulated hypotheses, collected evidence to test their hypotheses and answer their research questions. In each week of the four-week module, there was a 50-minute pre-lab lecture was delivered by the professor to introduce concepts and techniques that were used in the lab. The teaching staff for each lab section consisted of one graduate teaching assistant (GTA) and 3- 4 undergraduate teaching interns (UTIs). Each lab meeting lasted 3 hours. During the lab, students practiced using databases and bioinformatics tools with a given DNA sequence, for example the DNA sequence of the human hemoglobin. Upon completion of the module, each team created a poster to share the results of the self-selected research project with their classmates during a poster symposium as part of the lab. Each PI of the structural biology module wrote a research paper about their findings, which was then peer-reviewed by the other team members before it was graded by the staff at the end of the semester. The themes and schedule for the four labs in the structural biology module are presented in Table 3.1. This study mainly focused on the instruction during Lab S3, during which students discussed plans for their own projects with what they had learned in three weeks. It provided a good context for implementing the CADE framework that facilitates student to think about scientific evidence in a broader context beyond the classroom activities.

Table 3.1. Timeline and themes for the structural biology module

Timeline	Theme
Week 1	Lab S1: Overview of structural biology
Week 2	Lab S2: DNA to protein: Exploring the importance of sequence information
Week 3	Lab S3: Modeling protein structure from amino acid sequence
Week 4	Lab S4: Protein structure visualization

3.3.2 Participants

Two GTAs volunteered to participate in this study. The GTAs were both enrolled in doctoral degree programs in life sciences. One GTA (represented as GTA1) was a second-year graduate student. He designed the structural biology lab curriculum with the guidance from his major research advisor who was the lecture instructor of the structural biology module. The other GTA (represented by GTA2) was a graduate student in the final year of a botany doctoral degree program. They both had one-year experience of teaching the lab course being investigated before participated in the study, and both had taught the structural biology module in the 2019 Fall semester. Each GTA taught two lab sections during the investigated semester.

The two GTAs participated in three professional development (PD) meetings during the structural biology module. The PD mainly used the CADE framework as the material for guiding GTAs' understanding evidentiary reasoning and thinking about the instruction on scientific evidence during the structural biology lab investigation (see Appendix C for the PD material). Each PD meeting lasted about 1 hour. During the first meeting, the GTAs were presented with research results showing students' difficulties in evidentiary reasoning. They were introduced to the CADE framework and shown with the examples of CADE scaffolding questions designed by the researchers for the HWE investigation presented in chapter 2. The GTAs were then asked to design scaffolding questions for the structural biology module based on their understanding of the CADE framework. GTA1 volunteered in designing GES questions and GTA2 volunteered in designing DES questions. Together with the author as the educational researcher, participating GTAs modified the scaffolding questions (both GES and DES) during the second PD meeting. In the third PD meeting, GTAs worked together to implement designed scaffolding questions in lab instruction materials, including PowerPoint slides and the lesson plan. Each GTA randomly chose one of their two sections to implement the GES questions as the GES section and the other as the DES section during the week of Lab S3 (Appendix D for detailed GES and DES questions).

The participants who contributed to course improvements were paid for their participation. As their laboratory discussions were recorded, the laboratory instructor and student participants agreed to participate according to a protocol that was reviewed and approved by the Institutional Review Board (IRB#1702018760251).

3.3.3 Data collection and analysis methods

The GES and DES lab sections taught by the two GTAs were videotaped. By the end of the semester, each GTA was invited to have a semi-structured interview about their experience of implementing the CADE framework into their instruction, the example interview questions are presented in Appendix E. Each interview lasted about 60 mins and has been audiotaped. The videotaped lab instruction and audiotaped interviews were then transcribed using an online transcription tool, Trint.com, and proofread by the author.

GTA participation codes

The analysis of the lab instruction focused on the period during which the GTAs guided the GES/DES questions. The instruction in a single GES/DES question-led discussion was separated as a coding unit. It was then categorized into two parts: the initial question, which was the designed GES/DES question, and the following-up instruction, during which GTAs gave further explanations about the initial question, provided feedback to students' responses, or asked further questions based on the initial question or student responses.

Two sets of codes were applied to the following-up instruction to indicate the function of their statements as their participation and the evidentiary reasoning components presented in their statements. Codes of GTA participation were modified from the "Teacher Contribution to Reasoning Codes" (Furtak et al., 2010). Words, phrases, sentences or paragraphs of the instruction were coded and categorized into *Summarize*, *Comment*, *Prompt*, *Contribute* and *Challenge*. Descriptions of each code and example quotes are presented in Table 3.2.

Table 3.2. GTA participation code

Codes	Description	Example quotes
Comment	GTA makes comments on students' answers.	*"Nice, really good. That's a good answer."*
Summarize	GTA summarizes or repeat students' answers.	*"She said the structures are very, very similar."*
Prompt	GTA uses questions or hints for students to clarify their answers, provide other opinions or reach an agreement about an idea.	*"How long it takes, it is similar in size you said, like the folding pattern you're saying?"*
Contribute	GTA introduces their own idea about evidentiary reasoning to students, without asking students' idea.	*"When we perform any experiment, it has certain variables with which we can play around and we can get different kind of observation, different kind of outputs. And based on those results, we actually can draft a final conclusion with a certain degree of confidence."*
Challenge	GTA uses questions or hints for students to think about evidentiary reasoning beyond the initial questions.	*"So we have to know the different levels of structure right, from the primary to the quaternary, why do you think that's important?"*

In order to figure out what evidentiary reasoning components indicated by the CADE framework did the GTAs talk about or ask their students to think about during their instruction, the content under *Contribute* and *Challenge* were aligned with the Theory => Evidence relationships, Evidence <=> Data relationships and Evidence => Theory relationships of CADE framework and divided between disciplinary knowledge and epistemic considerations. The statements in other GTA participation codes don't have evidentiary reasoning components. Codes were counted and compared between GES and DES sections within and between the two GTAs to demonstrate the differences in instruction. The codes, descriptions and examples of evidentiary reasoning components are presented in Table 3.3.

Table 3.3. The codes of evidentiary reasoning components

Codes	Description	Example in "Contribute"	Example in "Challenge"
Theory =>Evidence relationships, Disciplinary Knowledge	Disciplinary knowledge in Theory=> Evidence relationships	"*So, for understanding homology modeling the very first thing, what you should understand at this point is how protein looks like, what protein is made up of.* *If we know what protein is made up of by now, but structurally how it is organized, that is something which you know, and there is a lot more which you should know about homology modeling and throughout this lab you will learn with me how we proceed for the homology modeling thing.*" *	"*So two structures may look similar, but what about the protein sequence of human and mouse hemoglobin when we come to protein sequence and structure?*" *
Theory => Evidence relationships, Epistemic Considerations	Epistemic considerations in Theory=> Evidence relationships	• Is relevant evidence used to render the question, hypotheses, plausible? • Are variables, relationships clear? • Is the articulated model complete, specific, and internally consistent? • Were alternatives evaluated?	• Is relevant evidence used to render the question, hypotheses, plausible? • Are variables, relationships clear? • Is the articulated model complete, specific, and internally consistent? • Were alternatives evaluated?
Evidence <=> Data relationships, Disciplinary Knowledge	Disciplinary knowledge in Evidence <=> Data relationships	"*In short, BLASTp is an algorithm, which considers your protein sequence as strings, strings as alphabetical characters, and it tries matching those characters using the database, which it is.*" *	"*Did you use the first one as a reference (in the BLASTp)? Why didn't you choose the second one? How about the others? Why didn't you choose the second one?*" *

Table 3.3. continued

Codes	Description	Example in "Contribute"	Example in "Challenge"
Evidence <=> Data relationships, Epistemic Considerations	Epistemic considerations in Evidence <=> Data relationships	"*And it (BLASTp) is mostly used, very widely used search engine, which is cited by different journals. So people trust this. So the data which we are getting, the result which you are getting from BLASTp is definitely credible, right? We agree on this point.*" *	"*So, from BLASTp you got one homolog which is a DNA polymerase. Just a makeup. Once you check with the SWISS model, the homolog is RNA polymerase. Which one should we trust?*" *
Evidence => Theory relationships, Disciplinary Knowledge	Disciplinary knowledge in Evidence => Theory relationships	"*It's like by looking at two structures, we can actually say this thing that okay, fine it is looking same.*" *	"*Were they (the two protein structures) exactly this similar when you compared?*" *
Evidence => Theory relationships, Epistemic Considerations	Epistemic considerations in Evidence => Theory relationships	"*And based on those results, we actually can draft a final conclusion with a certain degree of confidence.*" *	• Are conclusions internally consistent? • Is fit with other studies considered? • Are alternate interpretations evaluated? • Are limitations and uncertainties explicitly addressed?

Quotes labeled with * are examples from the participants' lab instruction. Underlined statements represent the ideas in the CADE framework.

Interview data

Thematic analysis approach was applied to the interview data (Clarke & Braun, 2017). Words, sentences and paragraphs were coded using the original words presented in quotes. Codes were summarized into categories, and themes were naturally emerged from these categories. The themes were compared with the lab instruction data to reveal how the GTAs implemented the CADE framework into their GES and DES sections for leading discussions about evidentiary reasoning.

3.4 Results

3.4.1 Participating GTAs had different instruction on guiding evidentiary reasoning

The GTAs participation codes were counted for the two GTAs in both of their sections (one GES and one DES) to summarize and compare differences in their instruction on guiding evidentiary reasoning (Figure 3.1). The phrase counts and percentage of GTA participation codes are shown in Table 3.4 for detailed information.

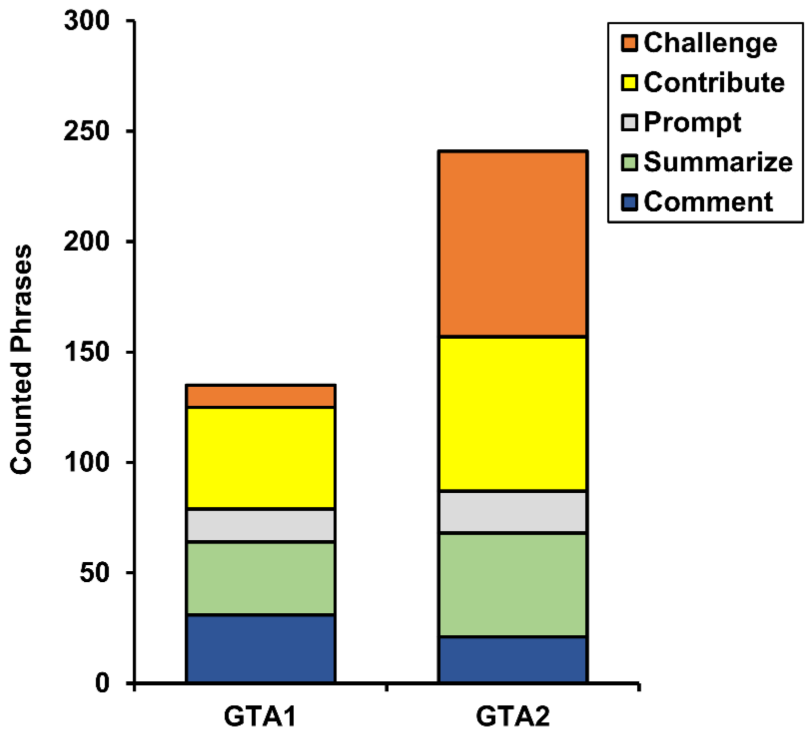

Figure 3.1. Comparison of the counts of GTA participation codes between GTA1 and GTA2.

Table 3.4. Counts and percentage of GTA participation code in all sections between GTA1 and GTA2

	GTA1		GTA2	
	Count	%	Count	%
GTA participation				
Challenge	10	7%	84	35%
Contribute	46	34%	70	29%
Prompt	15	11%	19	8%
Summarize	33	24%	47	20%
Comment	31	23%	21	9%
Total	135	100%	241	100%

The codes were summarized from the two sections (one GES section and one DES section) for both GTAs.

In general, GTA1 participated less than GTA2 (135 vs. 241, Table 3.4) when guiding the scaffolding questions on evidentiary reasoning. A large portion of both GTAs' participation in the following- up instruction is *Summarize* (24% of GTA1 and 20% of GTA2), which was due to that they were requested by the author to repeat and summarize students' answers to include students' ideas during the videotaping. The GTA2 participated more in the CADE discussions, especially in the *Contribute* and *Challenge* categories, 154 for GTA2 and 56 for GTA1 for both *Contribute* and *Challenge*. This indicated that comparing to GTA1, GTA2 intended to add more values in the discussions by contributing his own ideas about scientific evidence or challenging students' thinking by asking questions about scientific evidence to guide student thinking more about the scientific evidence. For example, after a student responded that they needed to know the different levels of protein structure to the initial question "*So based on what you have already learned, what should you do or what should you already know to investigate the homology modeling of your protein of interest?*", GTA2 followed up by asking "*OK, so we have to know the different levels of structure right, from the primary to the quaternary. OK. Now, why do you think that's important?*" (*Summarize* and *Challenge*) to guide the students thinking about the disciplinary knowledge in structural biology and to provide the reason on the significance of having protein structures as one variable for solving the problem of homology modeling.

3.4.2 The GES and DES questions influenced GTAs' participation

To understand the influences of GES and DES questions on GTAs' participation in the discussions, the percentage of each participation type between GES and DES sections of each GTA were shown in Figure 3.2.

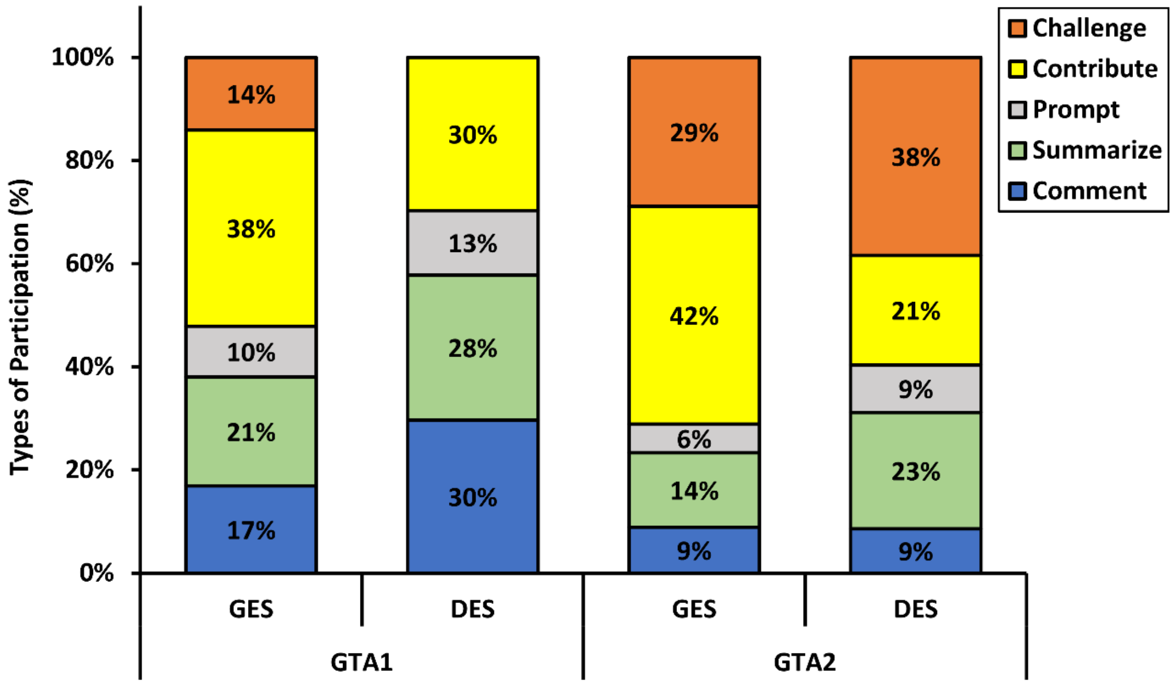

Figure 3.2. Percentage of GTA participation codes of GTA1 and GTA2 between GES and DES sections. The total numbers of counted phrases for GTA1 participation in GES section 71, in DES section is 64. The total numbers of counted phrases for GTA2 participation in GES section is 90, in DES is 151.

Comparing to the DES sections, the percentage of total *Challenge* and *Contribute* instruction increased in GES sections in both GTA1 (52% in GES vs 30% in DES) and GTA2 (71% in GES vs 59% in DES). This indicated that the discussions followed by the GES questions could prompt GTAs to add more values on students' thinking and using of scientific evidence during the structural biology investigation, which was partially due to the general nature of the GES questions, as it was stated by GTAs during interviews. The GTAs needed more explanations to help students understand the initial GES questions, since these questions didn't have the explicit terms or hints that directly link students thinking about scientific evidence to the biology or structural biology context. For example, with the initial GES question "*What must you already know about the variables you're going to look for in today's investigation?*", both GTAs contributed their knowledge about the hypothesis testing strategies and emphasized the importance of having the appropriate variables for the investigation. For instance, GTA1 explained and contributed his idea to that initial GES question by saying "*When we perform any experiment, it has certain variables with which we can play around and we can get different kind of observation, different kind of outputs. And based on those results, we actually can draft a final conclusion with a certain degree of confidence*".

GTAs' prior knowledge and research experience may also contribute and influence their instruction on evidentiary reasoning. Comparing participations in GES vs. DES sections, GTA1 took a dominant role in the discussion on the evidentiary reasoning in the DES discussion. He didn't ask any following up questions to students' response to challenge their thinking about evidence. For example, followed by the initial DES question "*How could you replicate or use possible alternative approaches for understanding homology modeling?*", GTA1 contributed his idea to students by introducing the advanced technologies in the structural biology area which closely related to his own research experience. He said "*So X ray crystallography uses a method called molecule replacement. Dr. Rossmann from Purdue, he contributed a lot in molecular replacement, which use homologous protein structure to determine the structure of a protein using X ray crystallography so still for that too, you need to find the homologous protein. The best alternative for homology modeling is data mining the structure straight, go and determine the structure using X ray crystallography, NMR, Cryo EM, that option is always there. So that is possible alternative*". This advanced disciplinary knowledge in structural biology, which was familiar to GTA1 who was a content expert, may be beyond students' understanding and prior knowledge. Thus, students were not able to conduct the necessary epistemic considerations about the reliability of this method and would not benefit from reasoning with this information for advancing sophisticated evidentiary reasoning skills.

When following up the same initial DES question, GTA2 used an example of the previous lab activity to refresh students memory about experimental replication and emphasized its importance. He said "*One hint, when we did the stomata hunt, I told you guys we could not rely on one single count of the stomata present, right? We should do multiple counts. Roughly at least 3 to 5 times replication, right?*". When introducing the alternative research methods, GTA2 guided students' thinking toward using the Swiss Model, a method that students practiced for experimental replications during the Lab S3. This disciplinary methodological knowledge was familiar to students and it would be more easily for them to connect with their epistemic considerations on the evidence generated by this method.

3.4.3 The evidentiary reasoning components in the GTAs' instruction

A second set of codes was applied to the content under *Contribute* and *Challenge* codes, to distill evidentiary reasoning components indicated by the CADE framework, in order to reveal aspects and components of the evidentiary reasoning, where GTAs provided values to classroom discussions about the initial GES and DES questions.

GTA contributed to the GES/DES sections in multiple aspects of evidentiary reasoning

From aligning the *Contribute* instruction with the CADE framework, it showed that the over 60% of ideas and knowledge that GTAs introduced to the students were related to the disciplinary knowledge in Theory => Evidence relationships and Evidence <=> Data relationships (Figure 3.3), even though the two GTAs contributed differently when guiding the GES and DES questions. For example, as a following- up to one student's prediction about the highly similar protein sequences led to the similar protein structures and functions, GTA1 contributed and added to student's response by saying that "*Comparing to the protein sequence and structure, the most conserved thing is the protein function*" (Theory => Evidence relationships, Disciplinary Knowledge), to help students understand the relationship between the amino acid sequence, protein structure and its function. There were few instructional statements about epistemic consideration in Evidence <=> Data relationships (Table 3.5) and in Evidence => Theory relationships. For example, when discussing about the confidence in using BLASTp for generating evidence, GTA2 said "*It's a scientific database and you can go look at the website link. The first thing is www and that's a website, right? Next, the following four letters are NCBI, which is a national genetic database. The other thing is that it's nationally trusted. Yes, we trust it, this data can be trusted*." (Evidence <=> Data relationships, Epistemic considerations) to contribute his idea about the reliability about the data source.

There was no instruction about the epistemic consideration in Theory => Evidence relationship in all sections for both GTAs, indicated that the participating GTAs didn't talked about the alternative models or theories, or other epistemic considerations when formulating a research questions or hypotheses.

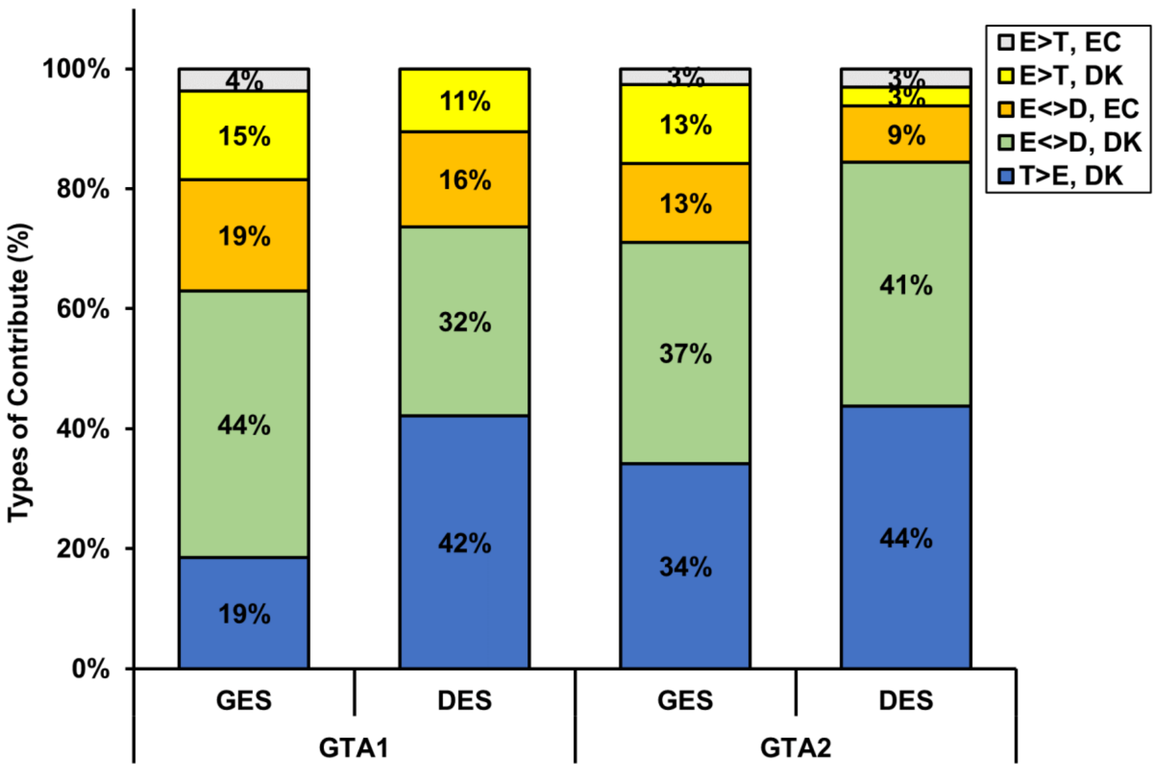

Figure 3.3. Percentage of GTAs' contribute aligns with the CADE framework. The total number of counted phrases of contribute instruction for GTA1 in GES section is 27, in DES is 19. The total number of counted phrases of Contribute for GTA2 in GES section is 38, in DES section is 32. In the figure key from bottom to top are, T>E, DK means Theory =>Evidence relationships, disciplinary knowledge; E<>D, DK means Evidence <=> Data relationships, disciplinary knowledge; E<>D, EC means Evidence <=> Data relationships, epistemic considerations; E>T, DK means Evidence=>Theory relationships, disciplinary knowledge; E>T, EC means Evidence=>Theory relationships, epistemic considerations.

Table 3.5. Counts and percentage of GTA contribute aligned with CADE in GES and DES sections between GTA1 and GTA2

	GTA1				GTA2			
	GES		DES		GES		DES	
	Count	%	Count	%	Count	%	Count	%
CADE components								
T>E, DK	5	19%	8	42%	13	34%	14	44%
T>E, EC	0	0%	0	0%	0	0%	0	0%
E<>D, DK	12	44%	6	32%	14	37%	13	41%
E<>D, EC	5	19%	3	16%	5	13%	3	9%
E>T, DK	4	15%	2	11%	5	13%	1	3%
E>T, EC	1	4%	0	0%	1	3%	1	3%
Total	27	100%	19	100%	38	100%	32	100%

T>E, DK means Theory =>Evidence relationships, disciplinary knowledge; E<>D, DK means Evidence <=> Data relationships, disciplinary knowledge; E<>D, EC means Evidence <=> Data relationships, epistemic considerations; E>T, DK means Evidence=>Theory relationships, disciplinary knowledge; E>T, EC means Evidence=>Theory relationships, epistemic considerations.

GTA challenged students' evidentiary reasoning influenced by GES and DES questions

Categorizing GTAs following-up questions that were used to challenge students' thinking about scientific evidence into the CADE framework components indicated that most questions used to challenge students thinking about the evidence during the structural biology investigation were about the disciplinary knowledge in Theory => Evidence relationships and Evidence <=> Data relationships (Figure 3.4 and Table 3.6) for both GTAs. For example, GTA2 asked students "*why are the molecular weight and PI point important (for your protein modeling project)? What is a molecular weight? What is the unit for your protein molecular weight?"*, to prompt students' thinking about relevant variables and their importance.

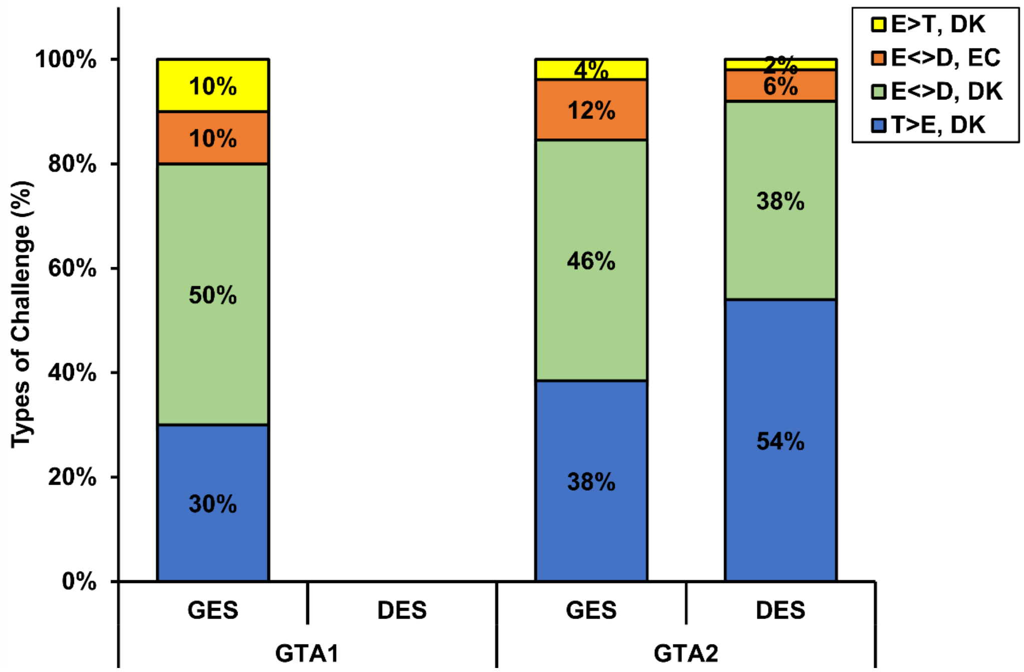

Figure 3.4. Percentages of GTA challenge align with the CADE framework. The total number of counted phrases of challenge for GTA1 in GES section 10, in DES is 0. The total number of counted phrases of challenge for GTA2 in GES section is 26, in DES section is 58. In the figure key from bottom to top are, T>E, DK means Theory =>Evidence relationships, disciplinary knowledge; E<>D, DK means Evidence <=> Data relationships, disciplinary knowledge; E<>D, EC means Evidence <=> Data relationships, epistemic considerations; E>T, DK means Evidence=>Theory relationships, disciplinary knowledge.

Table 3.6. Counts and percentage of GTA challenge aligned with CADE in GES and DES sections between GTA1 and GTA2

	GTA1				GTA2			
	GES		DES		GES		DES	
	Count	%	Count	%	Count	%	Count	%
CADE component								
T>E, DK	3	30%	0	0%	10	38%	28	54%
T>E, EC	0	0%	0	0%	0	0%	0	0%
E<>D, DK	5	50%	0	0%	12	46%	21	38%
E<>D, EC	1	10%	0	0%	3	12%	8	6%
E>T, DK	1	10%	0	0%	1	4%	1	2%
E>T, EC	0	0%	0	0%	0	0%	0	0%
Total	10	100%	0	0%	26	100%	58	100%

T>E, DK means Theory => Evidence relationships, disciplinary knowledge; E<>D, DK means Evidence <=> Data relationships, disciplinary knowledge; E<>D, EC means Evidence <=> Data relationships, epistemic considerations; E>T, DK means Evidence => Theory relationships, disciplinary knowledge.

Few questions (less than 10% for both GTAs in all sections) have been asked about the epistemic considerations in the Evidence <=> Data relationships. Neither of the GTAs followed up any questions about the epistemic considerations in the Theory => Evidence and Evidence => Theory relationships.

The two GTAs challenged student ideas differently when they guided the GES and DES discussions using follow-up questions (Table 3.6). GTA1 didn't ask any follow-up questions when guiding the DES discussions, while started to challenge students' idea when leading the GES discussion (the number of follow-up questions DES = 0, GES = 10). Whereas the GTA2 asked more follow-up questions in his DES section than the GES section (the number of follow-up questions DES = 58, GES = 26). The differences are probably due to their opposite attitudes toward the GES and DES questions they expressed during their interview, which are described in detail in the next section.

3.4.4 GTAs' experience of the CADE framework implementation

Both GTAs were interviewed to reveal their understanding about the CADE framework, as well as their experience in the design and implementation of GES and DES questions during the structural biology investigation.

GTAs thought positively on the CADE framework implementation

Both GTAs thought that the CADE framework was useful for guiding instruction even though they were facing challenges from trying to understand the CADE framework at the beginning of the study. Instead of using the CADE framework as an integrated guidance for evidence construction and evidentiary reasoning, both GTAs' understanding about the CADE framework was limited to the three relationships, Theory => Evidence relationships, Evidence <=> Data relationships and Evidence => Theory relationships, as well as GES/DES questions they have designed and implemented. Both GTAs mentioned that the CADE framework helped them deconstruct the complexity of the scientific process into three relationships, which made it easily for applying the CADE framework in teaching, and thus promote their students to understand the science process better during the investigation. For example, GTA2 said "*So I think when I used the CADE framework, it's pretty easy. I mean, at least the student will know about basic outline about what they should do for the next step. From the theory to the evidence, and then use data to go back to the theory*".

Both GTAs thought their students learnt well because of the implementation of the CADE framework in the structural biology module. GTA2 said *"… this (student's poster) indicates that students start to think, they're not just following the protocol to do the experiments, they have their own ideas…. They started to learn how to come up with a hypothesis before they do the experiments. It's not just mimicking and following the protocol. They have the hypothesis before they do it.*" Both GTAs reported that their teaching skills improved from implementing the CADE framework by asking GES/DES questions during the discussion and they would keep using these questions to prompt students to think about evidence in their future instruction. GTA2 said, "*I will keep asking questions, I'll post those questions to students before they do experiments. I'll keep using this strategy all the time. Once we have the questions during the lab activity, that helps students a lot, which I didn't do before. So I will keep using this one*".

The GTAs held opposite opinions toward GES and DES questions

Even though the participating GTAs appreciated the importance of using scaffolding questions to guide student thinking, they held opposite opinions toward GES and DES questions. GTA1 preferred using GES questions because he believed that GES prompted students to think more openly, and not limited to only the biology discipline. He said "*I found when you're asking*

GES, students were more open mindedly answering things … So my observation is they were not restricting themselves to the discipline when they were given more open question, which was allowing them to think about a lot out of the box”. However, he thought that DES questions prompted quick answers: “*when we were using DES questions, we were getting quick answers like, okay, you're asking this, this is how things work and this is what we did or this is how you should do*”.

GTA2 preferred the DES questions, he thought DES could draw students’ attention explicitly in structural biology and were easier to understand, whereas GES were too board for students to understand. He said “*I prefer DES, because I can give some examples such as Covid-19 (in my teaching). But for GES, they are kind of broad questions. Sometimes it's even hard for me to design the questions or to gather the students’ attention… GES are also good questions, but sometimes, some students would ask me for clarification, because for GES is kind of broad, it's not that easy to digest in several seconds*”. Their opposite opinions toward GES and DES questions may explain why they challenged student ideas differently when they guided GES and DES discussions using follow-up questions, which was described in Chapter 3.4.3.

3.5 Discussions

This study presented two cases of GTAs participated in professional development activities that facilitated them to design and implement scaffolding questions in their instruction using the CADE framework, to guide students thinking and reasoning with and about evidence during a structural biology lab investigation. Because GTAs play an important role in undergraduate biology education, especially in lab courses, understanding participant experiences of the CADE framework implementation will provide valuable implications for how we can integrate and support instruction on evidentiary reasoning in undergraduate biology lab courses.

As a comprehensive guide, the CADE framework unpacks the complex scientific evidence construct into practices and aligns these practices with the scientific investigation process, which includes generating research questions and hypothesis (Theory => Evidence relationships), designing experiments to collect data as evidence (Evidence <=> Data relationships), and drawing conclusions based on the evidence and compared with the existing theories and models (Evidence => Theory relationships) (Samarapungavan, 2018). The CADE framework is also a practical guild for undergraduate lab instruction that can not only be implemented in the design of course materials to provide students with activities and investigations emphasizing evidentiary reasoning (Chapter 2), but also provide necessary pedagogical supports for the GTAs to encourage students to think more about evidence as an essential learning objective. Scaffolding questions that are properly designed based on CADE can provide necessary supports for instructors to integrate evidentiary reasoning in their classrooms. Interviews on GTAs' experiences from participating in professional development activities indicated that both participating GTAs benefited from teaching with the CADE framework, as both reported improvement of teaching skills and student learning gains. The CADE framework helped shift learning and instructional focus of both students and GTAs from only the detailed procedural knowledge towards the whole picture of the research. Scientific investigations in the classroom should not be simplified and implemented as simply practicing procedural skills. More importantly, within these investigations, students should be given opportunities to construct and explore the alignments of phenomena, data and explanatory models in meaningful and purposeful ways, similar to what scientists are engaging in (Manz et al., 2020).

Instructor's belief and prior knowledge influence their use of instructional material, and will eventually affect students learning (Mcneill, 2009). With the same sets of CADE scaffolding questions, the two GTAs implemented them differently in terms of how they followed up in discussions. Overall, GTA2 had participated more in follow-up discussions led by the CADE scaffolding questions than GTA1, especially in contributing their own thoughts and ideas into the discussion and challenging students' ideas by asking follow-up questions in the discussions. Their preferences toward GES and DES questions expressed in their interviews explained the different performances when they challenge students' idea in GES and DES sections. These results indicate that GTAs' experiences, beliefs and preferences impact their instruction on evidentiary reasoning and their decisions on the aspect of scientific evidence they would guide students to think during their instruction.

GES and DES influenced instruction in different ways. Because of the general feature of GES, both GTAs provided more explanations on terms used in the questions, including variables, data or scientific evidence, to clarify students' understanding about the questions and prompt student responses. This may explain why there were more statements from the *Contribute* category from both GTAs, where they contributed their thoughts and ideas on scientific evidence into the discussions led by GES questions than DES questions. Even though the sophisticated evidentiary reasoning is tightly related to the disciplinary knowledge, including both the knowledge of theories and the knowledge of methodologies in a certain discipline, the knowledge about the general processes of science and its reliability has values in evidentiary reasoning (Clark A. & Ravit, 2018). GES questions can help the instructors who are content experts to steer more attention towards general hypothesis testing strategies. For example, GES questions helped shift GTA1's attention away from introducing advanced disciplinary knowledge to students, which may be beyond students' knowledge/cognitive level to understand and reason epistemically. Thus, including questions that prompt student thinking about the general knowledge of reasoning is still necessary for a course design to benefit both instructors and students.

The alignments of the GTAs instruction with the CADE framework indicated that most of their instruction still focused on the disciplinary knowledge, especially in the Theory =>Evidence and Evidence <=> Data relationships, the instruction about epistemic considerations were lacking in both GTAs in their GES and DES sections. Previous studies showed that the sophisticated forms of epistemic reasoning don't develop naturally even when the individual participated in inquiry learning or scientific research program and indicated the need of including well designed scaffolded discussions about epistemic thinking in the classroom (Samarapungavan et al., 2006; Sandoval, 2005; Sandoval & Morrison, 2003). The results of CADE alignments indicated the need for an emphasis on the epistemic consideration aspect of evidentiary reasoning in the professional development for GTAs and other inexperienced instructors, so that they could successfully support their student to advance evidentiary reasoning skills by connecting thoughts about the nature, scope and quality of evidence with disciplinary knowledge. The results also presented the lacking instructional guidance in the Evidence => Theory relationships. This indicated the need to emphasize on instruction of helping students drawing conclusions and interpretations from the evidence they got and comparing to the existing theories and models and at the same time discussing the sufficiency of the conclusions.

3.6 Limitations and Future Directions

This study presented examples from two GTAs. With the small sample of participants, this study does not support generalization. However, the two participants represented typical cases, with one participant was an expert in the structural biology discipline, have plenty disciplinary knowledge and research experience in the area, whereas the other participant was not. The comparison of these two cases helped understand the influence of the instructor's disciplinary knowledge and research background on teaching evidentiary reasoning. Their experience of implementing the CADE framework provided valuable implications on how to support the unexperienced instructors like the participant GTAs on guiding students' thinking and reasoning with evidence in their classes.

The future directions for integrating evidentiary reasoning in the undergraduate biology lab course should focus more on the supporting the instructors to get more comprehensive understanding about the scientific evidence construct as well as the CADE framework, especially emphasizing on including epistemic considerations about evidence in the teaching in order to support students in developing sophisticated skills on reasoning with and about evidence when they engage in the scientific investigations.

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CHAPTER 4. BIOLOGICAL REASONING ACCORDING TO MEMBERS OF THE FACULTY DEVELOPER NETWORK FOR UNDERGRADUATE BIOLOGY EDUCATION: INSIGHTS FROM THE CONCEPTUAL ANALYSIS OF DISCIPLINARY EVIDENCE (CADE) FRAMEWORK

4.1 Instruction

4.1.1 The purpose of undergraduate biology education

Undergraduate biology education has been shifting toward helping students to learn science through scientific practice and investigations. The current emphasis on integrating research-based instruction and authentic research experiences into undergraduate biology laboratory courses is meant to improve students' experimentation competence and critical thinking skills in the process of scientific investigation (AAAS, 2011; Laursen, 2019; Pelaez et al., 2017). This is important for a variety of reasons. Already 35 years ago, it was reported that few students had the opportunity to experience a demanding course at the undergraduate level designed to help them understand the logic of science including the knowledge and methods scientists apply to address major hazards to health such as climate change or disease (Koshland, 1985). More recently, during the COVID-19 pandemic, a science student described problems with understanding the process of science as being "about learning, getting it wrong, and then eventually getting it right" and learning that "when new evidence is constantly being acquired and published… the opinion of the scientific community can change" (Venezia, 2020). Venezia (2020) then pointed out some difficulties and that "making evidence-based decisions is absolutely crucial to an effective pandemic response."

Not all students have the opportunity to learn how disciplinary research techniques produce data that must be appropriately used as evidence, yet there is agreement that helping students learn about the generation and use of scientific evidence to advance scientific knowledge is critical (AAAS, 2011). Seymour and Hunter (2019) reported that changing teaching practices and student support strategies have made a difference according to findings from their sequence of two major studies of science students at the tertiary level in the US, but that variations in educational experience cause some science students to merely "survive" versus others that "thrive." Leaving many at an educational disadvantage. There continue to be reports that students have difficulty understanding the nature, quality, and scope of the evidentiary base that underpins scientific knowledge (Samarapungavan, 2018). Difficulties with understanding scientific evidence may help to explain public misunderstanding of mainstream science, such as vaccine safety. It is time, therefore, for biology educators at the tertiary level to include strategies known to effectively instruct students in the experimentation practices of rigorous research. Among the strategies being studied are undergraduate research experiences designed to induct students into the collaborative practices of science, reported in a number of studies to increase persistence in science and graduation rates for students in groups that have been historically under-represented in science (Seymour & Hunter, 2019). In line with these reports, hard work still needs to be done by biology educators to ensure that society is not left with policymakers and the general public who are unable to evaluate research-based solutions systematically, which leaves people without protection from being induced to act according to politics or the headlines instead of according to empirical evidence.

For the purposes of this chapter, we argue that an important aim of undergraduate biology education is to train people to understand biology as a research science, to understand the claims that are made based on evidence from modern research, and to evaluate and weigh the importance of those claims. Thus there is a need to teach students to reason with and about evidence upon which scientific claims are made and justified. Examples of difficulties students have with scientific evidentiary reasoning have been reported by others (see examples in Duschl et al., 2007; Ratcliffe & Millar, 2009; Labov et al., 2010). Books that focus on understanding scientific reasoning according to the philosophy of science have focused on disciplinary approaches to evidence evaluation and reasoning about causality in cases where causal claims have been established by research in a science discipline (Cartwright, 2007; Giere, 2006, Mayr, 2004). However, although education studies contextualized within biology as the subject matter have revealed the influence of disciplinary knowledge on students' evidentiary reasoning (Lewis & Kattmann, 2004; Pluta et al., 2011), there has been no systematic framework to guide educators who aim to help biology students to develop their evidentiary reasoning abilities until recently. Samarapungavan (2018) developed the Conceptual Analysis of Disciplinary Evidence (CADE) framework as a tool for educators by unpacking the notion of biological research evidence and how it is connected to contextual aspects of biology as a discipline.

4.1.2 The Conceptual Analysis of Disciplinary Evidence (CADE) framework

In order to identify important practices for helping students understand and use scientific evidence, the CADE framework (Samarapungavan, 2018) has been applied as a useful lens to categorize the practices that instructors can focus on scaffolding in order to advance evidentiary reasoning in undergraduate biology class discussions (Chapter 2 and Chapter 3). Derived from philosophy of science ideas about coordination of the models of theories and methodologies, here we use the term scientific evidence to mean the use of data by scientists to evaluate the similarity between scientific theories and the real world (Giere, 2006). The CADE unpacks the notion of evidentiary reasoning, a term we use to refer to the process of generating, using and evaluating evidence to solve problems and make claims. Students need to reason with and about scientific evidence in order to understand the nature, scope and quality of evidence of relevance to substantiate a claim (Samarapungavan, 2018). Because this definition of evidentiary reasoning encompasses the use of evidence at all stages of the research process, the CADE and evidentiary reasoning are more comprehensive than argumentation, which, according to Erduran, et al. (2015) refers to the justification of claims through evidence, and evidence-based reasoning according to Brown et al. (2010), which is the use of theoretical statements and scientific evidence to evaluate the quality of a claim. In the science education literature, evidence-based reasoning is not intended to model how scientific knowledge is generated by students or scientists (Brown et al., 2010). The CADE framework unpacks the complexity of scientific evidence and evidentiary reasoning about evidence in terms of four relationships: the Theory => Evidence relationships refer to the practice of formulating a research question, testable hypotheses, explanations or the rationale for an investigation; the Evidence <=> Data relationships refer to the practice of designing, executing, and analyzing investigations that generate useful data such as biological experiments; the Evidence => Theory relationships refer to the analytical processes that lead to inference and critical evaluation of the uncertainty or sufficiency of evidence and the appropriateness of scientific conclusions that are made and justified; and Social Dimensions refer to the communication of evidence to the public throughout the research process. Furthermore, for each of these four relationships, the CADE framework highlights two essential components of evidentiary reasoning, which are the relevant disciplinary knowledge and epistemic considerations. Disciplinary knowledge provides a foundation for evidentiary reasoning that must build upon a student's prior knowledge, theories and assumptions (Samarapungavan, 2018). It informs decisions about what knowledge is relevant to guide the research, what to choose as evidence and how to interpret the evidence. In parallel, epistemic considerations relate to the logical approaches to reasoning about the nature, scope and the quality of evidence in terms of the sources of such knowledge, its truth, limitations, and uncertainty surrounding the practices applied to generate the evidence for a scientific inference (Sandoval, 2005).

4.1.3 The Faculty Developer Network for Undergraduate Biology Education (FDN-UBE)

Reform efforts to integrate authentic research with undergraduate biology education are built upon the participation of scientists as instructors or curriculum designers in guiding students' scientific investigations. With their formally trained research experience, scientists can provide students with a relevant understanding of disciplinary biological knowledge and the sophisticated epistemic reasoning applied to experimentation skills essential for developing students' scientific practices. A subset of these expert biology educators have been actively working to create, build, support and sustain a community of practitioners and scholars to advance faculty professional development for undergraduate biology educators. Dr. Deborah Allen was Principal Investigator, Dr. Nancy Pelaez and I were external evaluators for a project funded by the National Science Foundation that was put together by scientists from different biology subdisciplines who lead faculty professional development to establish a Research Coordination Network, RCN-UBE: Faculty Development Network for Undergraduate Biology Education (FDN-UBE). With Gordon Uno, Karen Sirum, April Maskiewicz, Susan Elrod, and Charlene D'Avanzo as Co- Principal Investigators, since 2014 the project participants have shared biology faculty development resources, mechanisms, and research-based strategies, aiming to improve their delivery of professional development geared toward enhancing teaching and learning of biology across all higher education institutional contexts. Their rich experience in both teaching as well as faculty professional development provides insight about biology education and scientific practices related to improving students' understanding and use of scientific evidence. Implications from project findings provide lessons for young instructors and scientists regarding activities and practices for teaching biology in ways that help students develop evidentiary reasoning.

There is a paucity of reports from a faculty development perspective about what is needed to involve faculty members who are scientists to improve and support students' competence of understanding and using scientific evidence in undergraduate biology education. Thus we conducted an analysis of interview data for a study to document the value of scientists who conduct biology faculty development in terms of their experience and professional perspective. It was found that their knowledge and efforts aligned well with a focus on unpacking evidentiary reasoning in the process of undergraduate biology education in line with the CADE framework (Samarapungavan, 2018). Activities and practices that the faculty professional developers mentioned during interviews were analyzed through the CADE framework lens to reveal important components that the faculty developers brought to advance undergraduate biology education. Typical quotes from the interviews are presented as examples to reveal insights about important scientific practices for helping students understand and use scientific evidence from the faculty developers' perspectives in terms of their own experience.

Since the CADE framework values the role of disciplinary knowledge, it was useful to examine the contributions of FDN-UBE members in order to reflect on ways to develop more sophisticated approaches to teaching and learning of biology by unpacking the notion of evidence according to its disciplinary contexts. In this way, we report on contributions from FDN-UBE members that would not have been possible if professional development had been limited to programs at an institutional Center for Teaching and Learning where the professional development leaders lack the affordances from having a science background.

4.2 Research Method

This study was guided by several research questions:

1. What personally motivates/motivated network members to engage in professional development?
2. What professional paths did they take along the way to becoming interested in and effective at professional development for biology faculty?
3. What resources or indicators of success make FDN-UBE members feel qualified to be leading effective faculty development?

Participants drawn from the FDN-UBE membership consisted of 50 individuals who voluntarily responded to online surveys in 2015-2017. FDN-UBE members were asked to take part in this study if they had participated in at least one of the network's activities or attended a network synthesis meeting. They were invited by an email invitation or with flyers at the registration desk at an FDN-UBE meeting for participants to read and determine if they were interested in completing an online study recruitment survey. Survey and interview protocols were approved by the IRBs of Purdue University (protocol # 1510016672, N. Pelaez) and the University of Delaware (protocol # 575674, D. Allen).

Fifty individuals responded to online surveys that were conducted with questions about their motivation for joining the FDN-UBE project and about the major challenges and issues that a network such as the FDN-UBE could address. A final survey question was used for recruiting interview participants and then a stratified representative subset of the participants was selected for oral audiotaped phone interviews. Since interviews were conducted by phone it was possible to select volunteers for interviews to represent different regions in the US, different types of institutions, and a range of different biology sub-disciplines. A representative sample of 18 FDN-UBE network members participated in phone interviews that were recorded for up to 60 min in duration plus a follow-up interview to refine interpretations with assistance from a subset of the original sample who agreed to member-checking so that their words were interpreted as they intended. Results and quotes to illustrate the findings are from the 18 original interviews plus 10 follow-up interviews of representative participants.

The data collected were initially intended to answer research questions 1, 2 and 3 (above), but with our interest in understanding and exploring evidentiary reasoning in undergraduate biology education, an additional research question 4 was explored:

4. What model of professional practice represents the value added and additional potential contributions from FDN-UBE members who are engaged in biology faculty professional development to advance undergraduate biology education?

Guided by this research question, a second tier of data analysis with the CADE as a lens was aimed to reveal instructional practices that help students understand and use scientific evidence from FDN-UBE members' perspective.

4.2.1 Interview transcription and coding methodology

An open coding procedure as characterized by Strauss and Corbin (1990) was based on Khandkar (2009). Interview recordings were transcribed using Trint.com online, and then proofread individually. For a subset of the interviews, printed transcripts were cut into pieces for line-by-line coding (by 2 independent coders). Words, sentences or parts of the transcripts were labeled by topic names chosen from within quotes from the transcripts. Coded topic information was categorized based on similarity. After open coding, coded information from the same transcript was put into a spreadsheet to build a coding matrix. Category names were refined and defined by looking for patterns, discovered by comparing coded data from different interviews until saturation was achieved. Following this open coding process, a second tier of coding was conducted according to CADE where words, sentences or parts from the interview transcripts were categorized according to the four relationships present in the CADE framework as a model of professional practice. Quotes within each relationship were then coded as either disciplinary knowledge or epistemic aspects of reasoning. Any quote of relevance to reasoning about evidence in ways that call on disciplinary science knowledge was coded as Disciplinary knowledge in biology and items that relate to the quality of the evidence in terms of good general advice to an investigator regardless of their discipline were coded as Epistemic considerations. Before reporting any findings, participants were assigned pseudonyms. Survey and interview protocols were approved by the IRBs of Purdue University (protocol # 1510016672, N. Pelaez) and the University of Delaware (protocol # 575674, D. Allen). No identifying information is reported from the interviews. Summaries of the main points of the interviews are reported in the aggregate.

4.2.2 Selection of FDN-UBE volunteers for interviews

Participants who were interviewed were stratified and selected according to biology subdiscipline and to be representative of network subgroups focused in three areas:

Jump-Starting Early Career Faculty in Active Learning (Co-leaders: Mark Connolly & Gili Marbach-Ad). This group used Delphi study methods to develop a consensus among experts on what activities and conditions support adoption of active learning by early-career biology faculty. The study was aimed at producing four prioritized consensus lists: recommendations for individual faculty development in AL strategies; identification of obstacles or barriers; potential sources of support and assistance; and mechanisms that departments, colleges, and universities can adopt to encourage use of active learning approaches.

Inclusive Teaching Practices (Leader: Bryan Dewsbury). This group focused on design of a robust inclusive teaching professional development model to address increasing calls for a transformation of biology classroom culture to support more equitable and inclusive community to welcome students into science. Bryan Dewsbury, the leader of this effort, also successfully garnered support for a scaled-down version of an immersion model from the John Gardner Foundation.

Sustaining Change (Co-leaders: Rachelle Spell, Larry Blumer & Gordon Uno). This group was interested in how to connect faculty development efforts to systemic change initiatives on campuses, and what institutional factors help sustain implementation of best teaching practices learned in faculty development efforts. They developed and implemented a survey of institutional factors in sustainability of best teaching practices for institutions to use to review their efforts.

The experiences of teaching and professional development from the FDN-UBE members of these groups could provide insight of use to others who could include scientific practice and evidentiary reasoning as a focus for undergraduate biology education. By coding according to the Conceptual Analysis of Disciplinary Evidence (CADE) framework quotes from interviews of representative FDN-UBE members yielded data for answering the fourth research question. This enabled us to suggest a model of practice that represents value added and additional potential contributions from FDN-UBE members according to their current areas of professional focus. An aim for the future is to extend their cur-rent professional practice by identifying areas for potential future development of evidentiary reasoning in undergraduate biology education in areas not yet targeted. A contribution from this work therefore targets future development of new focus areas for faculty professional development aimed at supporting student reasoning with and about evidence to help future students develop abilities to make and critically evaluate the strength of inferences and claims in the biological sciences.

4.3 Findings from the Online Survey

Survey participants (N=50) reported leading a range of faculty professional development activities, from instructional design, workshop facilitation, education research, program evaluation, consultations at the department or program level, and graduate student/TA training. A relatively large proportion (Figure 4.1) report performing these activities in a context that is either outside of their institution or not part of their formal roles (“on my own”).

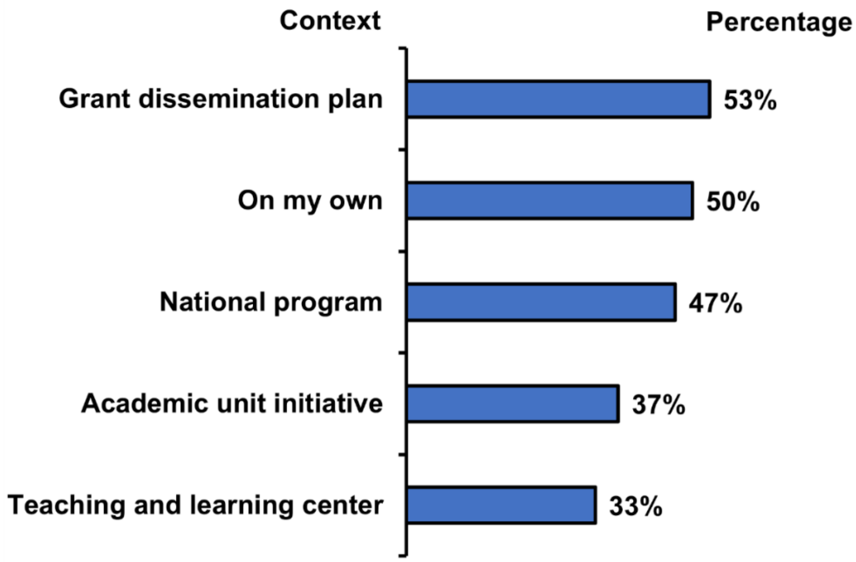

Figure 4.1. Context of members' past or present biology faculty professional development activities. The total number of participants is N= 50.

In addition to their membership in the FDN-UBE Network, according to their online survey responses, participants in the FDN-UBE network reported participating in the previous four years in three or more different types of events (on average) from an impressive array of more than 60 scientific or professional activities, listed alphabetically in Box 4.1.

Box 4.1. Scientific and professional activities reported by the FDN-UBE members

- Achieving the Dream Network
- Accelerating Systemic Change Network (ASCN)
- Advancement of Competence with Experimentation - Biology (ACE-Bio) Network
- American Association for the Advancement of Science (AAAS) events, such as Envisioning the Future of Undergraduate STEM Education (EnFUSE) and Pacific Coast meetings
- American Chemical Society (ACS)
- American Educational Research Association (AERA)
- American Society for Cell Biology (ASCB)
- American Physiological Society Institute on Teaching and Learning (APS-ITL)
- American Society for Microbiology Conference for Undergraduate Educators (ASMCUE)
- Association of American Colleges & Universities (AAC&U) High-Impact Practices (HIPs)
- Association of American Colleges & Universities (AAC&U) STEMCentral.net
- Association for Biology Laboratory Education (ABLE)
- Association of College and University Biology Educators (ACUBE)
- Association for Contemplative Mind in Higher Education (ACMHE)
- Bio-Link
- Biology Teaching Assistant Project (BioTAP)
- BioQUEST Curriculum Consortium
- Center for the Integration of Research, Teaching, and Learning (CIRTL)
- Community College Biology education research (CC-BER)
- Community College Biology Faculty Enhancement through Scientific Teaching (CCB FEST)
- Community College Undergraduate Research Initiative (CCURI)
- Council for Undergraduate Research (CUR)
- CUREnet network of people focused on course-based undergraduate research experiences (CUREs)
- Learning Assistant Alliance (LAA)
- League for Innovation in the Community College (League)
- Life Discovery - Doing Science Biology Education Conference
- National Academies Scientific Teaching Alliance (NASTA)
- National Association for Biology Teachers (NABT)
- National Association for Research in Science Teaching (NARST)
- National Centers: NIMBio
- National Conference on Race and Ethnicity in Higher Education (NCORE)
- National Evolutionary Synthesis Center (NESCent)
- National Institute for Staff and Organizational Development (NISOD)
- NIMBioS: National Institute for Mathematical and Biological Synthesis
- National Science Education Leadership Association (NSELA)
- National Science Teachers Association (NSTA)
- Network of STEM Education Centers (NSEC)
- POD Network: Professional and Organizational Development
- Partnership for Undergraduate Life Sciences Education (PULSE) Vision and Change Leadership Fellows
- Quantitative Undergraduate Biology Education and Synthesis (QUBES)
- RCN-UBE for Visualizations, Interactive Simulations, and Animations for Biology Learning & Instruction
- REIL-Biology: Research Experiences in Introductory Laboratory in Biology
- Society for the Advancement of Biology Education Research (SABER)
- VISABLI: Visualizations, Interactive Simulations, and Animations for Biology Learning & Instruction
- ScienceCaseNet: National Center for Case Study Teaching in Science

Ecological Society of America (ESA) Experimental Biology (EB) meetings European Association for Research on Learning and Instruction (EARLI) European Society for the Study of Evolution (SSE) European Society for Evolutionary Biology (ESEB) Gordon Research Conference on Undergraduate Biology Education Research Human Anatomy and Physiology Society (HAPS) Introductory Biology Project (IBP) International Conference of the Learning Sciences (ICLS)	Science Education for New Civic Engagements and Responsibilities (SENCER) Summer Institutes (SSI) Society for College Science Teaching Society for Integrative and Comparative Biology Society for the Advancement of Chicanos and Native American in Science (SACNAS) State or regional science education society events such as New England Education Research Organization (NEERO), North East Science Teachers Education Association, NW Biology Instructors Meeting (NWBio), Science Teachers Association of Texas, Wisconsin Society of Science Teachers Summer Institutes on Scientific Teaching

The majority, who are providing professional development expertise to other faculty, are themselves faculty members in departments of biology or other science disciplines, and most were not formally associated with the campus teaching and learning centers whose core mission is professional development (Figure 4.2).

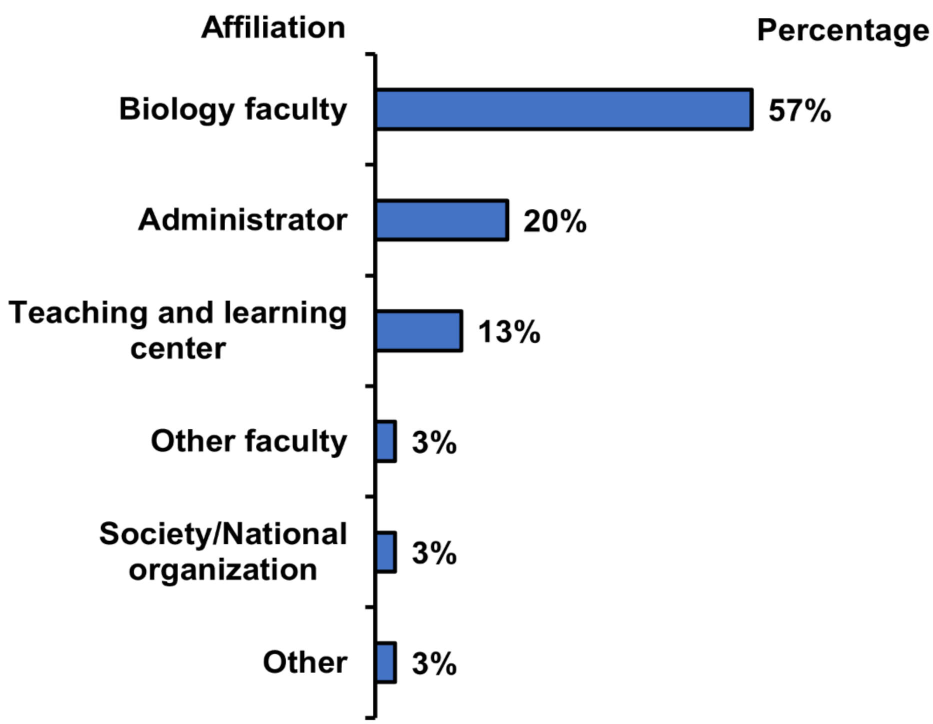

Figure 4.2. FDN-UBE members' primary professional affiliations. The total number of participants is 50.

4.4 Findings from the Interviews

All original and follow-up interviews were conducted between November 2016, and January 2018. Analysis of the interview transcripts in light of the research questions led to identification of several themes. Now, in 2021, a global pandemic has gripped the world and we face important questions about how to incorporate biology as a research science into our collective decisions. Surprisingly, our findings about the role of evidentiary reasoning from the faculty developers' perspective in this study show how well FDN-UBE members are positioned to sup-port other educators in providing students with relevant biology instruction essential for developing students' evidentiary reasoning about biological investigations. As illustrated below by sample quotes from the interview study participants, first we highlight three major themes:

- Faculty professional developers in biology education are visionaries/missionaries.
- The pathways toward education of biology faculty professional developers are unconventional but remain focused on biology as a discipline.
- Knowledge sources include but go beyond the professional development literature.

4.4.1 Biology professional developers are visionaries/ missionaries

Motivation for leading biology faculty professional development activities was often expressed in the context of an inspiring vision or progressive possibility:

> Phil: "I just think that in 10 years, the …. undergraduate biology education system is going to look dramatically different, and ….it needs to be driven by faculty…."

> Bill: "When I started as an undergraduate, I wanted to change the world, and so, you know, I thought 'so what can I do?' And I thought, well, you know, teaching is a reasonable thing to do and…. I think I'd like that."

> John: "I have a very clear and, you know, inspiring vision, to me at least, of what I think a university campus can look like and what it can contribute to a functional society. I think due to no one's particular fault, we have lost the way of it." (And later in the interview) "…but I think I would love that any student walking on any campus feels like this is a place they can come and really grow as a person. And our mission, or our teaching mission, is really dedicated to that."

Interviewees typically expressed almost a moral obligation to lead by providing professional development to biology educators:

> John: "…. if you are going to call for changes, you know, and you're going to accuse people of not having the necessary skills to lead that change, you know, part of this is you have a moral obligation to be part of the solution."

> Ellen: "I have no idea what motivates me. It just seems like you reach a point where that's what you should do. It seems that's part of the process of getting more senior in a profession."

> Motivations to engage in this work were often expressed as being intrinsic ones:

> Anna: "…they're coming to activities that I created. This is the first bonus for me."

> Ellen: "… when, for example I have a workshop on writing…. materials and somebody creates something that is just brilliant, completely outshines the 'professor'.…when I think I might have had a small part in just helping to create a setting where they feel they could do that… I find that very rewarding."

4.4.2 The unconventional pathways of biology faculty professional developers remain focused on biology as a discipline

While all of the interviewees received formal graduate education in some aspect of biology, at some point in their career trajectories, they incorporated professional development into their professional roles, not necessarily by design. Teaching and professional development in teaching became a satisfying way to pursue new interests and commitments, without turning their back on biology:

> Sarah: "In my experience, the getting into professional development ….is a little bit of a coincidence….it was not necessarily a track that you would say, oh, I would like to do professional development as that goal for me. It was a series of fortunate events."

> Anna: "So, they wanted me to continue in biology, but I felt like I love more that I can talk about what I am doing.... I love more science education than science. But it's not… like education as education alone, and science as science alone. I like the energy between science and education."

> Jill: "Well, the reason I went to her and said this is something I'm very interested in is it's actually a good percentage of what I do…. But I am actually the director of the intro sequence, ….and I took it on as an important service I wanted to provide to help make sure that it was a cohesive, collaborative, 'most effective way as possible' (teaching) group. (Later in the interview) … And because of my experiences and my success with helping faculty develop, I really would like to see my career grow in that way."

> John: I have officially left the…. biology [research] world behind. I mean, I loved it, but I just love this more (later in the interview) …. but it requires time, and it requires a different way to think about what a professor's responsibility is.

4.4.3 Knowledge sources include but go beyond the professional development literature to include oral traditions

In discussing knowledge sources used to acquire expertise in professional development, interviewees (29%) mentioned the literature, but also discussed the importance of oral traditions including personal interactions through attending workshops, conferences, and meetings, and through networks.

> Anna: "I'm looking at the literature all the time…."

> Ellen: "But we're forced to make people write on pieces of paper or the electronic version of that and create these dead documents and we value that more than this oral tradition that we have that's, that's been so impactful in science education."

> John: "…they are the ones who kind of pointed me to a workshop I could go to….to give me the kind of experience that quite frankly I think is what allowed me to get the job I have now. I kind of got into teaching and the scholarship of teaching and learning through the professional development world because they were - these were admin and so the organization was POD, and you know the way they think about scholarship was through professional development."

> Bill: "Participants apply to attend these workshops and they actually do the science….and they leave these workshops knowing this is something I can do in my class; I know how to do it and I know that it works. So it's, …. it's….to me it was really transformative….. And it really changed my point of view on what works and where our priorities should be."

> Sarah: "And also finding other people who were doing similar things and watching how they were doing it and then ultimately getting pulled into projects to work with people and hear how they were doing things."

> John: "That's…. where I think this becomes a really robust thing, because you're not just meeting to kind of check some ideas back and forth and it is good to see you. And let's talk about what happened at my institution versus yours. No it isn't one particular thing that if we kind of put all our collective intellectual power together we can have a much more powerful paper, a much more powerful workshop, or a much more powerful online training program or assessment scheme and ..."

Analysis of the interview transcripts illustrates that faculty professional developers in biology education are valuable visionaries. Through non-conventional career pathways, they disseminate knowledge through biology faculty professional development, and their knowledge sources are not limited to the professional development literature. In the words of one interviewee:

> Sarah: ‘today, I do not have, you know, a publication that we can point to, but we’re definitely working on formalizing a lot of what we know.”

4.5 Interview Findings Through the Conceptual Analysis of Disciplinary Evidence (CADE) Lens

The second tier of coding according to the CADE framework revealed important practices for helping students understand and use scientific evidence according to the professional developers’ responses to a question about what they viewed as an indicator of success in their faculty development work. They often described their success in terms of what they were aiming to accomplish for undergraduate biology education through leading professional development activities. The interviews were conducted before the Conceptual Analysis of Disciplinary Evidence (CADE) framework was published by Samarapungavan (2018). However, this framework was chosen because it mapped onto ideas about integrating authentic research into biology education for both major and non-major undergraduate students in ways that were reflected as indicators of success according to their professional biology faculty development experiences.

Half of the participants (9/18) explicitly mentioned authentic research practices in undergraduate biology education as having potential for increasing students’ interest in learning biology, improving students’ biology literacy, and retention to graduation even though they were asked about successful biology faculty development and not about biology instruction. For faculty members who are scientists and have formal scientific research experiences, the important thing is not only to help other educators teach students disciplinary knowledge in biology, but also “we should be teaching them how to do biology and what biologist do.”

> Julia: “So I think that thinking about that scientific teaching approach … that really emphasizes the use of practices within the disciplinary field and how it is that then improves the way that the students learn all the content and the practices of that discipline as well.”

4.5.1 Theory => Evidence relationships: A knowledge foundation for scientific research

The CADE framework emphasizes the role of disciplinary knowledge to the practice of formulating testable hypotheses, explanations or rationale for an investigation. Decisions about an investigation closely relate to the relevant disciplinary knowledge like theories, mechanisms, and causal relationships, as well as general knowledge about formatting research questions and hypothesis testing process. The Theory => Evidence relationships guide an investigators' decision about what kind of the important unsolved problem to investigate with and what variables are relevant with the investigation (Samarapungavan, 2018). It is important to focus on the knowledge that students need before guiding them through a scientific research experience in biology.

A focus on conceptual understanding

Deep conceptual understanding plays a role in evidentiary reasoning and undergraduate biology education. Helping students build meaningful conceptual understanding is one of the important components that participants mentioned that fits the Theory => Evidence relationships according to the CADE framework. When students gain deep understanding of the concepts in biology, they become able to organize their biological knowledge and information in a meaningful way. Although concept learning sets the basic foundation for scientific research practice, students have problems in remembering and understanding how to apply concepts and knowledge in biology.

> Steven: "What it is like it's obvious that students, no matter how many times they've learned they won't remember this, because to us, these facts have meaning, like a different molecule has directionality, and the directionality is important. But I think to students they're just random facts."

Clair also mentioned the need for the instructors to provide the knowledge and information in a meaningful way for the students.

> Clair: "They said they are worried about student engagement and their worry about helping to develop... they don't necessarily use the language, but helping students develop certain mental models that organize the information so they have this conflict between a lot of content and being frustrated because it's just develop(ing) the sort of organizational structure they need for it."

Several mentioned a pedagogical way for instructors to improve students' conceptual understanding is to track understanding using a concept inventory.

> Anna: "... one of the things to do is a concept inventory. We use that a lot. We created a concept inventory and we had like five years, maybe more than five now, worth of data from people of... in 8, 9 courses, it caused... interaction. And we gave the concept inventory before and after this course, and we learned that students are not getting it. And now we are working on that with activities."

However, when instructors apply a concept inventory in their teaching, other factors are also carefully considered, like an accurate assessment according to the expected and actual student performance level.

> Jill: "… you can't just do course inventory and you can't just concept inventory because there's no performance parameters associated with that. Those kinds of things only address knowledge maybe in skill, but it doesn't address to what level."

Use of cutting-edge research examples

When talking about activities and scientific practices that relate to the CADE Theory=> Evidence relationships, some participants mentioned the importance of including disciplinary knowledge about current science research, especially examples from the instructors' own research experience. Bob shared thoughts about his own teaching experience when he talked about using examples that are more relevant to the students to increase their interest in learning biology.

> Bob: "In bringing other examples, an example with more relevance to students, like examples in Texas, examples of your own work, you know, … whenever I talk about whatever I did, or all my colleague next door did, they just become more interested."

From a professional developer's point of view, Claire also suggested getting re-search examples into the classroom.

> Claire: "if you're leading a lecturer section right and then what you can do to get research into that classroom is to talk about your own research and they are perfectly comfortable doing that."

Learning about research was suggested to bring about an increase in students' learning motivations and improvement of their learning outcomes.

> Anna: "If the teacher makes students to want to stay in the field and to show that biology is an interesting topic, this is also important, especially in introductory courses".

4.5.2 Evidence <=> Data relationships: Practice analysis with authentic data

Evidence <=> Data relationships involve the practices of designing and conducting a scientific investigation. Knowledge and practices about data collection and data processing are only relevant when data are considered as useful empirical evidence. Two main themes were identified under the Evidence <=> Data relationships according to findings from the FDN-UBE participant interviews. They indicated advanced research techniques and also mathematical abilities as two types of specific skills or practices to be developed through undergraduate biology education to help students become capable of generating and collecting data as evidence for their scientific investigations.

Advanced research techniques for collecting data

As biology is a rapidly developing discipline, new research techniques and instruments are constantly emerging to meet the changes and challenges in biological investigations. Not only are students facing these challenges, but educators also need help keeping up with advanced techniques.

> Simon: "… think how much is it changed for people particularly at an undergraduate institution or community college, right? They're not getting exposed to modern techniques as frequently. And yet we're expecting that the students are getting exposed. So the faculty need a lot of content help as well."

Basic mathematical skills for analyzing data

Basic mathematical skills, like applying statistical methods and doing calculations, are competencies that enable students to analyze data. Although not formally the focus of what is taught as disciplinary knowledge in biology, mathematical skill, as a component of disciplinary knowledge in biology must be appropriately cultivated rather than being treated as a "weed out" skill, as it influences the accuracy of the data analyses and provides evidence for validity.

> Emily: "So how many biology programs require students to go through a year or more calculus? And then they just don't make it cause they can't do it. And they go, wow, I didn't pass calculus. It's not that they didn't pass biology. They didn't pass calculus."

> Simon: "So they've (collaborating instructors) created an introductory excel activity because they felt like their students needed some more ramping up before they could analyze the data as it was written in the lab originally."

> Judith: "with my math coworker… she wrote on a board some measurement that we were doing with some milliliters, in liters ....and she'd written some number times ten to the minus seventh (liters), and I went, wow, we would never do that. There's nothing that measures in ten to the minus seventh. We would write, you know 70 microliters or something, ... So we're using microliters."

In this last quote, Judith has recognized the discipline-specific approach to reasoning about measured volumes in biology and that this type of reasoning was not taught by a math coworker.

4.5.3 Evidence => Theory relationships: Sufficiency of interpretations

Engaging in practices for interpreting evidence involves considering how to learn from the evidence, whether interpretations are consistent with the totality of disciplinary knowledge available and if any alternate interpretations are compatible with the evidence.

> Ben: We "just give them thousands of photos, say go to look at all these for an hour and say what pattern do you see."
>
> Sarah: They "think about manipulating data and what it tells us."
>
> Anna considered "how to ... interpret trees or how to interpret figures. And then we gave them figures the same in the evolution course as in the genetics course. And every time you go deeper and deeper, understanding and asking more questions. But it's built on the same thing that they saw before."

4.5.4 Social dimensions: Communication of evidence to the public

In motivating students to engage in scientific practice, communicating evidence to the public is an important part of the entire process of scientific investigation. In the interviews, professional developers talked about the practices of collaboration and communication among students, including peer reviews and publication of results from an investigation. According to the professional developers, students who engage in these activities get deep understand of the evidence as they share ideas about scientific evidence with each other. Scientific communication also motivates students to engage in authentic research practice as members of a diverse and welcoming community.

> Ellen: "They (students) like working in groups. They like making their work public. And I think we can harness all those things."
>
> Bill: The students "do peer review, do revision…"
>
> Blake: For "a theoretical client ... they had to develop a sustainable agriculture method you know the principles you know biology or whatever hydroponics or whatever the kids dream of and making it work."

Peer review, revision, use of real-world scenarios, and public presentation of their work are strategies mentioned to support students in communicating their work to stakeholders. These mentions of science communication involve reasoning with and about evidence throughout the research process from the proposal stage to a report of their findings, sometimes with an audience (a theoretical client) identified.

4.6 Discussion and Implications for Future Direction

By understanding the role of evidentiary reasoning from the faculty developers' perspective in this study, we find that FDN-UBE members are well positioned to support other educators who provide students with relevant biological disciplinary knowledge essential for developing students' scientific research practices. The FDN-UBE network members we interviewed are motivated scientists who hold an inspiring vision of progressive educational possibilities. Their career trajectories were not very conventional, but they found opportunities to inform themselves and pursue their interests in biology with an aim to serve our biology education community. Their sources of knowledge include but go beyond the professional development literature to incorporate learning from meetings that target cutting edge science research, education research or practical pedagogical knowledge applied to higher education. At such meetings or from colleagues they have learned about professional development through oral traditions and from the example of others who are doing similar things, working with faculty to advance biology education.

A real problem most FDN-UBE members we interviewed are working on is the hard work of training undergraduate biology students to accept and deal with the uncertainty inherent to research. In lab instruction, it is easy for students and the instructor to recognize when they learn procedural knowledge, such as the structure of a heart including valves and muscle that propel blood through it, or how to pipette an accurate volume. From our personal experience, we know that students feel a sense of accomplishment when they recognize a well-organized course where they feel they really learned something concrete. However, the abstractions of reasoning about evidence are more difficult to recognize. The CADE framework was applied to reveal a value of FDN-UBE member contributions to biology faculty professional development as well as areas that still need to be targeted (i.e. Epistemic considerations). As a systematic framework of professional practice, the CADE framework can focus students and instructors on their accomplishments as they learn to reason with disciplinary knowledge and consider science epistemology in deciding what counts as evidence and how to use it (Samarapungavan, 2018). Educators could support students by using the CADE framework as a guide for discussions throughout the process of a research study that gives opportunities to investigate a knowledge gap; operationalize relevant treatment, control, and outcome variables for experimental design; apply scientific conventions and standards for precise and accurate measurement; make appropriate decisions about the research subject and sampling; use tools for aggregating and analyzing data such as statistics; and apply science conventions for representing and communicating ideas about evidence throughout the research process, from inception of a study to reporting the findings. In fact, the CADE framework is also applicable to research methods such as bioinformatics, structural biology, and evolutionary tree-thinking studies that are not based on experiments, although they do conform to a more generalized consensus research process (Thanukos et al., 2010).

We have also introduced the CADE framework as a lens that revealed what the FDN-UBE professional developers are doing that cannot be done in a more general way by any leaders in a Center for Teaching and Learning. Such faculty developers lack the required knowledge to incorporate a biological disciplinary perspective needed to ensure society is supported by policymakers and a general public who can understand and evaluate biological evidence for research-based solutions. In order for biology instructors to guide students' development of reasoning with and about scientific evidence during the process of biological experimentation, instructors need to clarify how evidentiary reasoning happens throughout the entire research process. The CADE framework highlights the need to be explicit about disciplinary knowledge, as well as the need to focus on helping students to incorporate more sophisticated epistemic reasoning in their approaches to biological research for success in the shift toward helping students learn the biological sciences through scientific practice and investigations. The FDN-UBE members who are experienced professional developers in this study were trained formally as scientists, they have passions about biology teaching and faculty professional development in biology education as an indispensable part of their career, and they focus on scientific practices related to all four CADE components of evidentiary reasoning in biology. Their experience of doing research in biology that they bring to biology education and faculty professional development allows the participants to have insights about the educational reform of learning biology through scientific practices. Their ideas and suggestions about helping students understand and use scientific evidence make them a valuable resource for other faculty who want to engage in biology education and involve evidentiary reasoning in their teaching.

In summary, four points are offered to improve biology students' opportunities to develop better reasoning about evidence:

- In case there is no faculty professional developer who is a biologist in your institution, attend meetings listed in the findings from this study to benefit from the oral traditions passed on by experts like FDN-UBE members. They are passionately assisting biology educators beyond their own departments and they share innovative ideas about shifting biology lab instruction toward more authentic research experiences that will support students in learning to reason with and about evidence, promoting the application of disciplinary knowledge and science epistemology to biological experimentation.

- Adopt and implement CADE as a systematic framework to support a shift in professional practice toward more sophisticated epistemic reasoning in the teaching and learning of biological sciences. By unpacking the multifaceted nature of evidence and the complex integration and coordination of disciplinary knowledge with epistemic considerations, the CADE framework can guide evidentiary reasoning education in biology.
- Conduct studies to collect detailed data on how faculty professional developers understand CADE and how they integrate CADE with their prior experiential pedagogical and disciplinary knowledge in working with undergraduate biology educators to improve evidentiary reasoning in biology.

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CHAPTER 5. CONCLUSION

This dissertation presented three qualitative studies for understanding scientific evidence and integrating evidentiary reasoning in the undergraduate biology education through the lens of the CADE framework. These studies provided practical examples of instructors using scaffolding questions in supporting evidentiary reasoning during the lab investigations, explored how different types of scaffolding questions that aiming disciplinary knowledge or general knowledge of reasoning influenced instructors leading the discussions on scientific evidence. These findings provided implications for faculty professional development for supporting guiding evidentiary reasoning in the future. This final chapter focuses on the contributions, limitations and the future directions of the research.

5.1 Contributions

5.1.1 Integrating evidentiary reasoning in teaching Hardy-Weinberg Equilibrium

The first study presented a novel classroom investigation along with the assessment for teaching Hardy-Weinberg equilibrium (HWE) in an introductory biology lab course. Informed by the Conceptual Analysis of Disciplinary Evidence (CADE) framework, this investigation targeted at improving students' evidentiary reasoning skills and provided students with the detailed disciplinary knowledge underpinning to support their thinking and reasoning with evidence. Instructors can easily apply the scaffolding questions designed with CADE during the investigation. The changes in the instructor's lab discussions showed that the implementation of CADE inspired the instructor to engage students in thinking multiple aspects of evidentiary reasoning, as well as prompted students' epistemic considerations about the construction of scientific evidence. This study also showed that the CADE framework can be a practical guide for integrating evidentiary reasoning in the classroom discussions.

5.1.2 Integrating evidentiary reasoning in teaching structural biology

Built on the understanding from the first study about the important value that CADE can bring to a lab investigation, the second study tried to understand the CADE implementation from the graduate teaching assistants (GTAs) experience and explored how disciplinary knowledge (represented by the DES questions) and general knowledge of reasoning (represented by the GES questions) influenced how participating GTAs guided discussions during a structural biology investigation. This study provided an example by using CADE for professional development as a pedagogical support to the GTAs. Findings from this study pointed out the need for supporting epistemic considerations during evidentiary reasoning in instruction. This study also discussed the value of general knowledge on the instruction of using scientific evidence. Together, this study contributed to the practical knowledge of providing pedagogical training with CADE via professional development for GTAs, as well as designing efficient instructional questions to support instructors in leading discussions on evidentiary reasoning in the classroom.

5.1.3 Understanding evidentiary reasoning practices from members of the FDN-UBE network

This study used the CADE framework as an analytical lens for revealing valuable practices aiming at advancing students' evidentiary reasoning from experiences of FDN-UBE members. Members of FDN-UBE participated in various types of institutions and professional development activities. Their experiences in designing and implementing courses and activities to improve students' using and reasoning with scientific evidence provided valuable insights for understanding the evidentiary reasoning practices in a broader context and provided important implications for supporting instructors on teaching evidentiary reasoning in the future.

In summary, I presented examples of implementing the CADE framework in two biology subdisciplines, one was teaching HWE and one was guiding a structural biology lab investigation. Findings from lab instruction as well as GTAs' interviews showed that CADE can be a practical framework to guide lab investigations. In Chapter 2 and Chapter 3, scaffolding questions designed for the HWE investigation and the structural biology investigation were provided for other instructors to use in the same learning context. Table 5.1 is a handout designed based on the CADE framework for instructors to design their own scaffolding questions on evidentiary reasoning for other investigations.

Table 5.1. A handout for designing CADE scaffolding questions

Evidentiary practices	Disciplinary knowledge	Epistemic considerations
Theory => Evidence Relationships Model Articulation: Formulate/test hypotheses or pose explanations and a rationale for the investigation		• Considering the various models, which is most appropriate to address your research question and why? • What would count as evidence to address your research question? • What limitations are associated with the evidence? • What additional evidence would give more confidence?
Evidence <=> Data Relationships Designing, executing, analyzing evidence from investigations		• What variables are relevant? Why is this data appropriate? • Are the technical data collection procedures adequate? •Are data sampled in an unbiased way that is representative of the population? •Why did you set this specific alpha-level for the statistical test? Would other levels be appropriate? •What do you think of the quality of your data for answering the research question?
Evidence => Theory Relationships Models of argument: Sufficiency of conclusions		•How confident are you in this explanation? •How confident are you that Ho should have been rejected/not rejected? •Are there any alternative interpretations to explain the findings? •Do the findings fit with other reports from published studies?

The first column of Table 5.1 is the evidentiary reasoning practices aligned with scientific inquiries and investigations. The third column includes questions that prompt epistemic considerations about constructing scientific evidence, which were used and tested in this dissertation. In the second column, instructors can design the questions that prompt students to think about disciplinary knowledge of evidentiary reasoning based on the CADE framework. Instructors can design these questions based on the context of the investigation, and different learning objectives.

5.2 Limitations

There are several limitations for the studies in this dissertation that should be addressed in future studies for better understanding and integrating evidentiary reasoning in multiple disciplines of undergraduate education. First, participants observed in the first two studies for implementing the CADE framework were teaching assistants in an undergraduate lab course. Additional efforts are needed to explore professional development approaches that support different types of instructors and teachers with various educational and research background in using the CADE framework as a comprehensive guide for integrating evidentiary reasoning in their teaching and fulfilling their instructional objectives.

Second, the idea to engage disciplinary knowledge and epistemic considerations in the CADE framework that advances the evidentiary reasoning can be transferred and applied to other disciplines, despite that CADE used the biology discipline as an example in this dissertation. Because the context for this dissertation was biology subdisciplines, more research is needed to test and integrate CADE in other disciplines, like chemistry or physics, to explore how to support evidentiary reasoning differently in other science disciplines.

Last, the first two studies that implemented the CADE framework were conducted at an R1 university. There is a need for testing CADE in other institutional settings, including community colleges and liberal arts colleges. This was also mentioned by members of the FDN-UBE in Chapter 4 to exam efficient instructional methods for advancing students' evidentiary reasoning ability during scientific investigations.

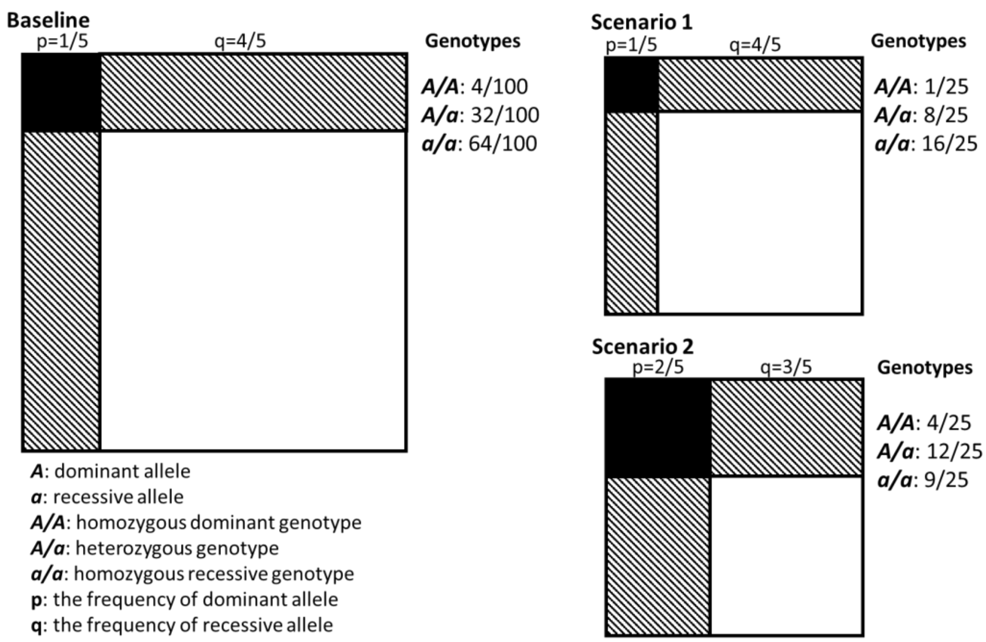
5.3 Future Directions

Future research should be conducted to address the limitations described above or to extend studies presented in the dissertation to new directions. First, social dimensions as one important practice in constructing scientific evidence were not studied in this dissertation. Research efforts are needed to understand how students communicate evidence with their peers, scientists or other audience. Second, because studies in the dissertation focused on the instructional perspectives, future studies should focus on students' learning on evidentiary reasoning guided by the CADE framework. There is a need to develop an assessment system to evaluate the quality of students' evidentiary reasoning in the process of scientific investigations, because evidentiary reasoning cannot be measured simply by the structure or components of a single claim or explanation.

By addressing the limitations and applying the CADE framework in various disciplines and multiple undergraduate research contexts, for example the individual research experience, courses or a whole training program, the development of evidentiary reasoning skills will benefit students in their academic performance as well as improve their scientific literacy for preparing the science careers and advancing decision-making skills in everyday life.

APPENDIX A. A HANDOUT FOR USING WITH FIGURE 2.1

As disciplinary background, compare two scenarios of population change where one maintains a phenotype ratio of 36% dominant and 64% recessive so it could have remained in Hardy-Weinberg Equilibrium (HWE) whereas the second illustrates a change not in HWE where the dominant phenotype increased to 64% with only 36% of the population still with the recessive phonotype.



The three squares (Baseline, Scenario 1 and Scenario 2) represent three hypothetical populations with the focus on one Mendelian trait that contains two alleles in one locus, illustrated by *A* and *a*. HWE applies to changes in allele frequency for the population over time as follows: The Baseline population contains 100 individuals with a frequency of the dominant allele, represented by p, as 1/5, and the frequency of the recessive allele, represented by q, as 4/5. Since there are only two alleles for considerations in this case, $p + q = 1$. There are 64 individuals with the recessive phenotype so 36 have the dominant phenotype. Of these, HWE predicts 4 of the dominant phenotype individuals to be homozygous dominant and 32 to be heterozygous. In Scenario 1, assume the baseline population declines to a population with only 25 individuals, still with p = 1/5 and q = 4/5. The allele frequencies did not change in this scenario, so the population could be in HWE because even though the total number of homozygous recessive individuals has declined, 16/25 with the recessive phenotype in Scenario 1, this represents the same recessive allele frequency as 64/100 in the baseline population. In contrast, assume for Scenario 2 that the Baseline population declines to a population that also contains 25 individuals, but the frequencies for dominant allele, p, is changed to 2/5, and q is changed to 3/5. The population in Scenario 2 is not in HWE compared to the baseline population. Scenario 1 and Scenario 2 can be used to illustrate the allele frequency changes for two populations in different places sampled from PetFinder.com. Even though both of the populations could have been derived from one population that was in HWE, a sample of each population containing 25 individuals could illustrate differential changes between the two populations. Scenario 1 population has 16 individuals with the homozygous recessive genotype (*a/a*) and only 9 individuals with the dominant phenotype (*A/_*). The phenotype frequency of homozygous recessive (q^2) is 16/25, so the frequency of recessive allele, q is 4/5 and allele frequency of the dominant allele, p = 1- q or 1/5. The Scenario 2 population has only 9 individuals with the homozygous recessive genotypes (*a/a*) and 16 individuals with dominant phenotypes (*A/_*). The genotype frequency of homozygous recessive (q^2) is 9/25, so the frequency of recessive allele, q is 3/5 and allele frequency of dominant allele, p = 1- q which is 2/5. Students could use the genotype counts calculated with the data from the two populations to conduct a Chi-square test to reject the null hypothesis that genotype frequencies in these two populations are not different.

APPENDIX B. SCAFFOLDING QUESTIONS USED IN THE HARDY-WEINBERG EQUILIBRIUM (HWE) LABORATORY INVESTIGATION

1. We have learned of two genetics models - Mendelian genetics and population genetics with Hardy Weinberg Equilibrium. What are the assumptions for both of them? Can you use either model? Which one is more appropriate and why?
2. What would a biologist think count as evidence for a genetics research prompt, and what sort of data would be collected? Why is this evidence appropriate to study populations? Are there any limitations associated with this evidence? What additional evidence would give a biologist more confidence?
3. Prompt: Discuss a sampling strategy that is not biased.
4. When performing a hypothesis test to test your model, how would you decide what it means when you fail to reject your null hypothesis? (Why did you set this specific alpha-level? Would other levels be appropriate?) If your Ho is rejected, what would biologists think is the most likely explanation, considering HWE assumptions? How confident are you in this explanation? Why would a biologist believe that would affect the genetics model? How confident are you that Ho should have been rejected?

APPENDIX C. HANDOUT FOR PROFESSIONAL DEVELOPMENT TRAINING

Categories of evidentiary relations in the CADE framework

Theory to Evidence (T to E)

Framing, identifying variables according to a set of potentially testable models.

Evidence ⇔ Data (E ⇔ D)

Disciplinary practices for inquiry (sampling, instrumentation, measurement).

Evidence to Theory (E to T)

Interpretation/evaluation of evidence from investigations and considering limitations.

SOURCE: Samarapungavan, Pelaez, Clase, Gardner, & Rogat, NSF award #1661124

Types of scaffolds

- **General evidence scaffolds (GES):** Questions, hints or prompts that label and draw students' attention to key aspects of evidence **but without explicit links to disciplinary knowledge. GES** Help students think more about the nature and quality of evidence in the context of their learning tasks.
- **Disciplinary evidence scaffolds (DES):** Questions, hints or prompts that label and draw students' attention to key aspects of evidence **with explicit links to disciplinary knowledge.**

For the EBE instructors

Bring your ideas to our discussion next week about:

1. What type of scaffolds you want to apply in your instruction?
2. What questions or hints you want to use, according to the scaffold you choose?
3. Which part of the instruction do you think will fit the CADE framework and is suitable for videotaping?
4. What additional material do you need for this teaching this module?

Timeline for these two weeks:

Feb 3 (Mon): discuss a time for a PD meeting before Thursday; decide one type of scaffolds you want to design with; think about the questions and hints you want to use.

Feb 5 (Wed): one hour of PD meeting together; ***time:***

Feb 6 (Thu): send your lesson plan with one type of scaffolds.

Feb 7 (Fri): the researchers will discuss and modify the scaffolding questions you designed and send back to you.

Feb 10 (Mon): Finalize lesson plan with DES and GES scaffolds; Define which times in the lab are discussions recorded.

Feb 11 (Tue): videotape section 002 and 003.

Feb 14 (Fri): videotape section 008 and 009.

Types of scaffolds

- **General evidence scaffolds (GES):** Questions, hints or prompts that label and draw students' attention to key aspects of evidence **but without explicit links to disciplinary knowledge. GES** Help students think more about the nature and quality of evidence in the context of their learning tasks.
- **Disciplinary evidence scaffolds (DES):** Questions, hints or prompts that label and draw students' attention to key aspects of evidence **with explicit links to disciplinary knowledge.**

For the EBE instructors

Bring your ideas to our meeting about:

5. Which part of the instruction do you think will fit the CADE framework and is suitable for videotaping?
6. What type of scaffolds you want to apply in your instruction?
7. What questions or hints you want to use, according to the scaffold you choose?
8. When you apply the CADE framework to the instruction of structural biology, which questions do you think are useful? Is there any part in the CADE framework is missing in the context of structural biology?
9. Beside the materials we have right now, which are lab slides of Lab S3, the lesson plan, reading materials for students, what additional material do you need for this teaching this module?

Please read all the materials before our meeting.

Timeline for these two weeks:

Feb 3 (Mon): discuss a time for a PD meeting before Thursday; decide one type of scaffolds you want to design with; think about the questions and hints you want to use.

Feb 4 (Tue): one hour of PD meeting together.

Feb 6 (Thu): send your lesson plan with one type of scaffolds.

Feb 7 (Fri): the researchers will discuss and modify the scaffolding questions you designed and send back to you.

Feb 10 (Mon): Finalize lesson plan with DES and GES scaffolds; Define which times in the lab are discussions recorded.

Feb 11 (Tue): videotape section 002 and 003.

Feb 14 (Fri): videotape section 008 and 009.

For the EBE instructors: talking about the scaffolding questions and you experience of implementing the CADE framework.

1. Talking about your experience, how did you use the CADE framework to design your questions?
2. When implementing the CADE framework, which parts of the framework do you think are useful? Is there any part in the CADE framework is missing in the context of structural biology?
3. How confident do you feel to implement the CADE framework?

APPENDIX D. GENERAL EVIDENCE SCAFFOLDS (GES) QUESTIONS AND DISCIPLINARY EVIDENCE SCAFFOLDS (DES) QUESTIONS FOR THE STRUCTURAL BIOLOGY LAB INVESTIGATION

General Evidence Scaffolds (GES):

1. What must you already know about the variables you are going to look for in today's investigation?
2. How similar do you expect the data to be from those two research subjects? What do you expect to find in the evidence?
3. Is previous technique credible? How do we know if these sources are trustworthy? How might you replicate the process of data collection and analysis to increase the confidence in your findings?
4. In order to confirm your findings, what different tools would be applied to all the variables and in what order?
5. What has been learned from the evidence you got today? How will you share your data so that you have enough evidence to convince others of your finding?
6. How do the findings from Lab S2 add to what you've learned about your protein of interest today? How do you know when you have provided enough evidence in your poster?

Disciplinary Evidence Scaffolds (DES):

1. What must you already know about proteins to investigate homology modeling of your protein of interest?
2. How similar do you expect two sequences must be to have the same function? What predictions could you make if proteins have a similar function?
3. How credible are the BLASTp results? How could you replicate or use possible alternative approaches for understanding homology modeling? Why should we use SWISS-Model?
4. In research that involves the process of protein homology modeling, what online tools would a biologist use and in what order?
5. What has been learned from the homology modeling evidence you got today? How will you share your findings with others so they will be convinced of what found out about your protein based on homology modeling?

6. What do the molecular weight and pI findings from Lab S2 add to what you've learned about your protein of interest today? How do you know when you have enough evidence in your poster to convince others about what you found?

APPENDIX E. INTERVIEW QUESTION EXAMPLES

1. Could you describe how did you use the CADE framework to help you design your scaffolding questions? How do you understand the CADE framework?
2. Which parts of the CADE framework do you think are useful to design scaffolding questions for the structural biology investigation?
3. What are some challenges that you have experienced when applying the CADE framework in designing scaffolding questions for the structural biology investigation?
4. We selected a few typical posters and classroom responses from your students. Some of their ideas showed good reasoning and some revealed difficulties. Look at these answers from your students.
    a. What do you think about their ideas and reasoning?
    b. What aspects of evidence did you encourage your students to think about as they engaged in reasoning and problem solving during the structural biology investigation, especially when they were doing the homology modeling?
    c. What are some challenges that you have experienced in trying to teach students to understand and use scientific evidence in the structural biology investigation, especially when they were doing the homology modeling?
    d. How do you think about the two types of scaffolding questions, GES and DES, that you used in your instruction in the structural biology investigation?
    e. What are some of the specific things that you feel your students learned well because of the GES prompts that you used for that lab?
    f. What are some of the specific things that you feel your students learned well because of the DES prompts that you used for that lab?
5. What are some of the things that were challenging or difficult for your students to learn from these activities in structural biology module? (Follow-up if needed: what aspects of reasoning with evidence were hard for your students?)
6. How do you think participating in the professional development of implementation of the CADE framework may influence your ideas and plans for teaching in the future?

VITA

Chaonan Liu

Education

- **Ph.D., Biology Education** Jan. 2018 – Dec. 2021 (expected)
  Purdue University, West Lafayette, IN, USA
  Dissertation: *Integrating Evidentiary Reasoning in the Instruction of the Undergraduate Lab Research Course*
  Thesis Committee: Nancy Pelaez (Chair), Trevor Anderson, Stephanie Gardner, Selcen Guzey
- **M.S., Cell biology** Aug. 2009 – Jun. 2012
  Beijing Normal University, Beijing, China
  Thesis: *Bioinformatics analysis and biochemical characterization of Lilium longiflorum Formin1*
- **B.S., Bioscience**, **specialization in teaching** Aug. 2004 – Jun. 2008
  Ludong University, Yantai, China
  Thesis: *The Design of an Online Cell Biology Course*

Academic Honors and Awards

- Ross Fellowship, Purdue University 2018
- Outstanding Graduates, Shandong Provincial Department of Education 2008
- Outstanding Intern of Graduates, Ludong University 2008
- Teaching Skills Competition, *First Prize*, Ludong University 2007
- National Encouragement Scholarship, China Ministry of Education 2007
- Student of Academic Records, Ludong University 2007
- Merit Student, four times, Ludong University 2005 – 2008
- First-class Professional Scholarship, four times, Ludong University 2005 – 2008
- Shandong Province Government Scholarship 2005

Research Experience

- **Research Assistant**, Purdue University 2018 – present

Project 1. Implementing the Conceptual Analysis of Disciplinary Evidence (CADE) framework into curriculum design, professional development and instruction in a first-year undergraduate biology Course-based Undergraduate Research Experiences (CUREs). Understanding the influence of the CADE framework implementation on students' ability of reasoning with evidence during the scientific investigation.

Supported by National Science Foundation under grant #1661124.

Project 2. Understanding the experiences and motivations of the faculty development practitioners for undergraduate biology education.

Supported by National Science Foundation under grant #1346567

- **Research Assistant**, Beijing Normal University 2010 – 2012

  Predicting the structure and function of Formin1 protein identified from *Lilium longiflorum*. Purifying Formin1 protein using a recombinant protein expression system and characterize the biochemical function of the protein.

  Supported by National Natural Science Foundation of China under grant #31130005 and the National Basic Research Program of China under grant #2013CB126902

Publications

Published

Li, S., Dong, H., Pei, W., **Liu C.**, Zhang, S., Sun, T., Xue, X., and Ren, H. (2016) LlFH1-mediated interaction between actin fringe and exocytic vesicles is involved in pollen tube tip growth. *New Phytologist*, 214(2), 745-761. https://doi.org/10.1111/nph.14395

Submitted or in revision

Liu, C., Dreger, D. L., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. The Conceptual Analysis of Disciplinary Evidence (CADE) framework as a guide for evidentiary reasoning: A practical implementation in a Hardy-Weinberg Equilibrium (HWE) laboratory investigation. (***In revision, Journal of Biological Education, Jan. 2021***)

Liu, C., Pelaez, N., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., and Allen, D. Aspects of biological reasoning according to members of the faculty developer network for undergraduate biology education: Insights from the Conceptual Analysis of Disciplinary Evidence (CADE) framework. *Trends in Teaching Undergraduate Students to Do Research* *in the Life Sciences: Putting research into practice to drive institutional change*. (***Submitted, Book chapter, Jan. 2021***)

Liu, S., **Liu, C.**, Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. A framework for evidentiary reasoning: Insights from integrating evidence scaffolding in an undergraduate biology lab focused on evolutionary tree-thinking. (***In revision, CBE-Life Science Education, Oct. 2020***)

Liu, C., Mukherjee, I. A., Chang, L., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. A case study about collaborations and communications between scientists and educational researchers during the implementation of the CADE framework into teaching structural biology in a laboratory course. (***In prep, intended for CBE-Life Science Education***)

Liu, C., Mukherjee, I. A., Chang, L., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. Implementation of the CADE framework into structural biology teaching and learning in an introductory laboratory course. (***In prep, intended for Journal of Science Communication***)

Presentations

Liu, C., Mukherjee, I. A., Chang, L., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. Integrating evidentiary reasoning into a structural biology investigation in an undergraduate biology laboratory course. (2021) *7th Life Discovery – Doing Science Biology Education Conference*. ***Invited presentation***

Liu, C., Dreger, D., Liu, S., Samarapungavan, A., Gardner, S. M., Clase, K. L., Pelaez, N. The Conceptual Analysis of Disciplinary Evidence (CADE) Framework as a Guide for Evidentiary Reasoning during a Hardy-Weinberg Equilibrium (HWE) Laboratory Investigation. (2021) *The Society for the Advancement of Biology Education Research (SABER)*. ***Invited presentation***

Cai, C., Sapp Nelson, M., **Liu, C.** Connecting with undergraduate research: A pilot to tailor data literacy workshops in a library-led summer undergraduate research experience program. (2020) *Research Data Access & Preservation Association Summit*. Santa Fe, NM, United States. ***Invited poster***

Liu, S., **Liu, C.**, Gardner, S., Samarapungavan, A., Clase, K., Pelaez, N. Learning in the laboratory with evolutionary tree – thinking about blood parameters from model biomedical research organisms. (2019) *Experimental Biology 2019*. Orlando, FL, United States. ***Invited presentation***

Liu, C., Samarapungavan, A., Clase, K. L., Gardner, S. M., Liu, S., Flowers, S., Pelaez, N. Understanding potential problems with theory understanding and theory application when undergraduate students test the Hardy-Weinberg Equilibrium model with zebrafish. (2019) *Society for the Advancement of Biology Education Research West 2019*. Irvine, CA, United States. ***Invited presentation***

Liu, C. and Cai, C. Where are those college students who play "DOTA" now: talking about professional development in college. (2018) *Jinan University Forum*. Jinan, China. ***Invited presentation***

Pelaez, N., **Liu, C.**, and Allen, D. Towards becoming a professional development practitioner for undergraduate biology education. (2017) *Undergraduate Biology Education Research – Gordon Research Conference*. Easton, MA, United States. ***Invited poster***

Teaching Experience

- *BIOL20300 Human Anatomy and Physiology*, Graduate Teaching Assistant
  Purdue University 08/2021 – 12/2021
- *BIOL13500 First Year Biology Laboratory*, Graduate Teaching Assistant
  Purdue University 08/2018 – 12/2018
- *BIOL13500 Professional Development workshops*, Facilitator
  Purdue University 08/2018 – 12/2019
- *Cytoskeleton System*, Graduate Teaching Assistant
  Beijing Normal University 09/2009 – 01/2010
- *Eighth Grade Biology*, Intern Teacher
  Jinan KaiYuan Middle School 03/2008 – 05/2008
- *Microteaching for High School Biology*, Student Teacher
  Ludong University 08/2007 – 01/2008

Mentoring

Undergraduates

- Anna Hallowell 2020

- Becca Shelley 2020
- Alex Spector 2020
- Hannah Melchiorre 2018

Certificates

- Quality Matters (QM) Certificate: Independent Applying the QM Rubric 2021
- Safe Zone Training, Purdue University 2021
- NVivo 2020
- Trint (AI audio transcription software) 2017
- Teacher's license (high school level), China 2008
- National Computer Rank Certificate
  Level 3 - C Programming based network technology 2005

Service

- **Planning Committee**, Annual Conference for Key Laboratory of Cell Proliferation and Regulation Biology, Beijing Normal University 2010 – 2011